

COMP BOOK

Titan Master Blk.

I.

80 SHEETS • 10x7½ • 5x5 QUAD • 43-475



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Carl Sagan

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Faint handwritten notes at the top of the right page, possibly bleed-through from the reverse side. The text is illegible due to fading.

Brin + Jim say: k (thick): Ed Patterson, Do. Ind. Tech. ⁽⁷⁾
Atlanta [integrating sphere; he specializes in powder when
things are optically thick]. W. less spectral resolution.
Bob Carlson, U. Wash., Seattle [optically thin
transmission, S_{low} sphere: he will send glass for deposition; Patterson
may be able to use our angles.]

Outline Colloquium 11/19/81, Cornell

Convergence prebiol. org. chem. + plan. explor.

Miller electrodes. "Intractable polymer." Tholin: 6k "muddy".

a.a.'s. $\text{HCN} \rightarrow$ a.a.'s, purines, pyrimidines.

Adenine \leftarrow 5 HCN ; 30% yield in NH_3 ↓

50 ninhydrin pos. peaks, cf. 20 nat. occur'g a.a.'s.

Poss. applic. chondrites, Φ 's, outer s.s., i.s. matter.

Titan:

Kuiper $\lambda > 0.6 \mu$

Veverka: no neg. branch pol. curve, $\Phi \leq 6^\circ$.

Red color-index

\Rightarrow 1970 organic clouds. Cf. 1973 Ames conf.

C_2H_2 , C_2H_4 , C_2H_6 emission \Rightarrow atmos. inversion.

Variety models P_s , T_s , atmos. compos. Ice tectonics?

Voyager

Voy 1: 6500 km, ~ 1 km/lp

2: 100x range: 660,000 km.

♂ option.

No breaks.

But low contrast, surface organics? $\therefore O/V, O/CH_4$.

$\bar{v} > \text{several}, f < 10^{-5}$.

Atmos. structure

Spark, uv, Titan tholins

Expt'l set-up. Oxidation crust, electron probe analysis.

Bimodal a: 10's μ , 0.1's μ .

$n_c \approx 1.6, n_i \sim 10^{-2}$ ✓

Vis. spectrum, 0.36 - 0.6 μ .

Rages: Kuiper band apparent match $\lambda > 0.6 \mu$.

Thermograv. analysis; separable tholin components

(13)
Atmos. Compos. ^(uv N_2, N_2) More \rightarrow limb, not just sec γ effect.
Miller/Sagan early exp'ts.

Philosophy: absol. reaction rate kinetics vs. thermo.
equilib vs. exp't.

Pyrolytic GC/MS. Obs. selev. volatile components.

Synthesis during pyrolysis? [cf. T spark]

Lability C-C, e.g. Indolact. NH_2 .

Can its spectrum be understood as superpos. pyrolyzates?

Spark tholin pyrolyzates

Conjugated double bonds \rightarrow carotene [C_{40}] + congeners

Indole \rightarrow melanin

Pyrrrole \rightarrow chlorophyll + hemoglobin

Build's blocks chief biol. coloring agents are present.

Uv tholin pyrolyzates

Explan. its spectrum

cf. $(HCN)_n$

Rayleigh scattering \Rightarrow parts. at 1 mb level

UV IUE spectrum featureless; spark tholin. \sim featureless.

Effect heating lowers albedo, destroys features.
UV, vis, ir: "bottled clouds Titan."

~~T~~ 80% in η magnetosphere, 20% in solar wind.

Also c.r.'s + uv. Magnetosphere dissoci. \sim uv phdis.

$$10^{10} \text{ phdis s}^{-1} \times m_H \times \mu \times \phi \times t / \rho$$

$$= 10^{10} \times 1.67 \times 10^{-24} \times 3 \times 10 \times 1 \times 10^{17} \text{ s} / 1 \sim 5 \times 10^4 \text{ g cm}^{-2}$$

\sim 1 km layer organics.

Prebiol. org. chem. in deep freeze.

But maybe not. $\rho \times R$ Titan cf. Enceladus.

Tidal heating Titan: H₂O solutions surface or subsurface.

Titan Bulk Properties

Orbital radius, $20.4 R_s \approx 20.4 \times 60,400 \text{ km}$
 $\approx 1,232,000 \text{ km}$.

Radius to solid body surface: $2560 \pm 26 \text{ km}$ from Tyler et al.
Value adopted: 2575 km

Radius to $T_{\text{min}} = 2625 \text{ km}$, 50 km above surface,
roughly 100 mb level

Optical limb radius (cloud "tops"), allowing for air mass ~ 20 ,
 2815 km ,
roughly 0.3 mb level

Bulk density $\rho \approx 1.9 \pm 0.06 \text{ g cm}^{-3}$

$$g = \frac{GM}{R^2} = \frac{G \rho \frac{4}{3} \pi R^3}{R^2} = \frac{4}{3} \pi G \rho R$$

Solid body: $g = 4 \times 6.67 \times 10^{-8} \times 1.9 \times 2.575 \times 10^8 = 137 \text{ cm s}^{-2}$.

T_{min} : $g = 137 \left(\frac{2575}{2625} \right)^2 = 131 \text{ cm s}^{-2}$

Cloudtop: $g = 137 \left(\frac{2575}{2815} \right)^2 = 115 \text{ cm s}^{-2}$

Location	R (km)	P	g (cm s ⁻²)
Surface	2575	1.6 bar	137
T _{min}	2625	100 mb	131
Cloudtop	2815	0.3 mb	115

$$H = kT/mg \quad T_s = 91^\circ\text{K} \quad T_{\min} = 75\text{K} \quad T_{\text{ct}} = 172\text{K}$$

$$m = 28.5 \mu_{\text{H}} = 2.88 \times 10^{-23} \times 1.67 \times 10^{-27} = 4.8 \times 10^{-23} \text{ g}$$

$$\therefore H_s = \frac{1.38 \times 10^{-16} \times 9.4 \times 10^2}{4.8 \times 10^{-23} \times 1.37 \times 10^2} = 1.97 \times 10^6 \approx 20 \text{ km}$$

$$H_{\min} = \frac{1.38 \times 10^{-16} \times 7.5 \times 10^2}{4.8 \times 10^{-23} \times 1.31 \times 10^2} = 1.65 \times 10^6 \approx 17 \text{ km}$$

$$H_{\text{ct}} = \frac{1.38 \times 10^{-16} \times 1.72 \times 10^2}{4.8 \times 10^{-23} \times 1.15 \times 10^2} = 4.3 \times 10^6 \approx 43 \text{ km}$$

Critical $T_{\text{CH}_4} \approx 190^\circ\text{K} \Rightarrow$ we are always below T_c on Titan.

Melting the Surface of Titan

$$1 \text{ Kt TNT} = 4.2 \times 10^{19} \text{ ergs} \quad (4.2 \times 10^{12} \text{ joules})$$

$$\text{Present nuclear arsenals} \sim 20 \text{ Mt} \times 10^3 \\ \sim 8.4 \times 10^{26} \text{ ergs} \quad [\sim 10^{27} \text{ ergs}]$$

$$C_p (\text{water}) \approx 1 \text{ cal g}^{-1} (\text{K}^\circ)^{-1} = 4.2 \times 10^7 \text{ ergs g}^{-1} (\text{K}^\circ)^{-1}$$

$$C_p (\text{ice, } -150^\circ\text{C}) \approx 0.2 \text{ cal g}^{-1} (\text{K}^\circ)^{-1} = 0.84 \times 10^7 \text{ ergs g}^{-1} (\text{K}^\circ)^{-1}$$

$$\text{Heat vaporization water} \approx 2.3 \times 10^3 \text{ joules/g} \approx 2.3 \times 10^{10} \text{ erg g}^{-1}$$

$$\text{Heat fusion ice} \approx 80 \text{ cal g}^{-1} = 3.4 \times 10^9 \text{ erg g}^{-1}$$

\therefore to bring 1 g Titan surface ice to liquid state requires

$$L + C_p \Delta T = 3.4 \times 10^9 \text{ erg} + 4.2 \times 10^7 (1.8 \times 10^2)$$

$$= 1.1 \times 10^{10} \text{ ergs, or a factor several less}$$

To bring it from 94°K to vaporization requires

$$\approx 4 \times 10^{10} \text{ ergs.}$$

$$\text{Area Titan} = 4\pi R^2 = 8.3 \times 10^{17} \text{ cm}^2$$

\therefore melting to a depth of 1 cm requires $9 \times 10^{27} \sim 10^{28}$ ergs,

so existing nuc. weapons stockpiles can't do it; too puny by a factor $\gg 10^8$. [They melt a mm]

What mass of impacting comet can? Take $20 \text{ km s}^{-1} = v$.

$$10^{28} \text{ ergs} = \frac{1}{2} m v^2;$$

$$m = \frac{2 \times 10^{28}}{4 \times 10^{12}} = 5 \times 10^{15} \text{ g} \Rightarrow$$

$$\frac{4}{3} \pi r^3 \rho = m; \quad r^3 = \frac{5 \times 10^{15}}{4} \quad [\rho = 1]$$

$$r \sim 100 \text{ meter radius.}$$

To melt 10 m depth requires 10^3 more energy, $10 \times$ larger radius
 $\therefore r \sim 1$ km impacting object, size of typical nucleus.

More efficient would be a comet that was loosely bound and broke up into ^{few} small pieces on entry. The fragments would punch through the organics, vaporize the ice, and the resulting H_2O/CH_4 greenhouse effect would sustain the high temps, & spread them laterally. Best case would be simultaneous impacts from several directions

\therefore Q. for Shoemaker: waiting time for coll. 1 km comet w. Titan.

Also crater depth & calc. greenhouse w. resulting new atmos. structure.

For terraforming [not quite; this is more "bioforming"], rendezvous w. an \oplus -crossing \Leftarrow w. aphelion at γ . There, heliocentric v. is low. Thrusters Δ orbit until \Leftarrow captured by γ . Then graze γ atmos. to increase v immediately before coll. w. T.

Sromovsky et al. argue that the chromophores responsible for cloud contrasts lie between 100 mb level + surface. Is this consistent w. haze condensation τ 's? How does it affect τ_{ra} argument?

Breaks in Clouds

If deep break, should show up on monochromatic (non-ratio) image as bright pixels. Factor τ (a shades gray) should easily show. Clouds have low albedo. \therefore should not require too much Δp to increase τ_{ra} sufficiently at short λ . [Note fine particles might however obscure at blue but not at red λ 's:

$$l = \pi = \frac{2\pi a}{\lambda} ; \lambda = \frac{2\pi \times 2 \times 10^{-4}}{1} = 1.2 \times 10^{-4} \text{ cm} = 1.2 \mu.$$

In a N_2 atmosphere, Rayleigh scattering extinction coeff.:

$$k = 350 (n-1)^2 / N \lambda^4 \text{ cm}^{-1},$$

where n = refractive index, N is mols. cm^{-3} (Loschmidt. no. equivalent) + λ is in cm [Allen, Ap. Q., 3rd ed., p. 119].

For \oplus at sea level, $N = 2.7 \times 10^{19} \text{ cm}^{-3}$, $\lambda = 0.3 \mu = 3 \times 10^{-5} \text{ cm}$.

$$\begin{aligned} n-1 &= 2.88 \times 10^{-4} + \frac{1.629 \times 10^{-6}}{\lambda^2} + \frac{1.36 \times 10^{-8}}{\lambda^4} \quad [\lambda \text{ in } \mu] \\ &= 2.88 \times 10^{-4} + 1.81 \times 10^{-5} + 1.7 \times 10^{-6} \\ &= 3.1 \times 10^{-4} \end{aligned}$$

$$\begin{aligned} \therefore k &= 350 (3.1 \times 10^{-4})^2 / 2.7 \times 10^{19} \times (3 \times 10^{-5})^4 \\ &= \frac{3.5 \times 10^2 \times 3.1^2 \times 10^{-8}}{2.7 \times 10^{19} \times 8.1 \times 10^{-14}} = 1.54 \times 10^{-6} \text{ cm}^{-1} \end{aligned}$$

$$H \approx 8 \text{ km} \Rightarrow \tau_{ra} \sim 1.23 \checkmark$$

$$e^{-\tau_{ra}} \approx 0.29$$

∴ need Titan scale heights (v.p. 19)
 also need $N: p = NkT; N = p/kT$

$$N_s = \frac{1.6 \times 10^6 \text{ dynes cm}^{-2}}{1.38 \times 10^{-16} \times 9.4 \times 10} = 0.12 \times 10^{21} = 2.1 \times 10^{20} \text{ cm}^{-3}$$

[7.8 x Loschmidt's no.]

$$N_{min} = \frac{1 \times 10^5}{1.38 \times 10^{-16} \times 7.5 \times 10} = 0.10 \times 10^{20} = 1.0 \times 10^{19} \text{ cm}^{-3}$$

$$N_{ct} = \frac{0.3 \times 10^2}{1.38 \times 10^{-16} \times 1.72 \times 10^2} = 0.13 \times 10^{17} = 1.3 \times 10^{16} \text{ cm}^{-3}$$

∴ k determined for 0.3 μ, 0.55 μ, 0.8 μ

λ	$\frac{1.629 \times 10^{-6}}{\lambda^2}$	$\frac{1.34 \times 10^{-8}}{\lambda^2}$	$n-1$
0.3 μ	1.81×10^{-5}	1.67×10^{-6}	3.08×10^{-4}
0.55 μ	5.39×10^{-6}	1.49×10^{-7}	2.93×10^{-4}
0.8 μ	2.55×10^{-6}	3.32×10^{-8}	2.91×10^{-4}

Surface:

0.3 μ $k = \frac{3.5 \times 10^2 \times (3.08)^2 \times 10^{-8}}{2.1 \times 10^{20} \times (3 \times 10^{-5})^4} = \frac{0.195}{20} \times 10^2 = 20 \times 10^{-8}$

0.55 μ $k = \frac{3.5 \times 10^2 \times (2.93)^2}{2.1 \times 10^{20} \times (5.5 \times 10^{-5})^4} = \frac{1.56 \times 10^{-2}}{2.56} \times 10^2 = 1.6 \times 10^{-8}$

0.8 μ $k = \frac{3.5 \times 10^2 \times (2.91)^2}{2.1 \times 10^{20} \times (8 \times 10^{-5})^4} = \frac{3.45 \times 10^{-3} \times 10^2}{2.5 \times 10^2} = 0.35 \times 10^{-8}$

Cloudtops:

0.3 μ $k = \frac{3.5 \times 10^2 \times (3.08)^2}{1.3 \times 10^{16} \times (3 \times 10^{-5})^4} = 3.16 \times 10^{-1} \times 10^6 = 3.15 \times 10^5$

Clearly a problem w. Allen's eq.: N must be in numerator, not denominator. \therefore scale by N to Titan

From \oplus :

$$0.3\mu: k = \frac{350}{2.7 \times 10^{19}} \frac{(3.08 \times 10^{-4})^2}{(3 \times 10^{-5})^4}$$

$$= 130 \times 10^{-19} \times 0.117 \times 10^{12}$$

$$= 1.52 \times 10^{-6} \text{ cm}^{-1}$$

$$0.55\mu: k = 130 \times 10^{-19} \frac{(2.93 \times 10^{-4})^2}{(5.5 \times 10^{-5})^4}$$

$$= 130 \times 10^{-19} \times 0.0094 \times 10^{12}$$

$$= 1.22 \times 10^{-7} \text{ cm}^{-1}$$

$$0.8\mu: k = 130 \times 10^{-19} \frac{(2.91 \times 10^{-4})^2}{(8 \times 10^{-5})^4}$$

$$= 130 \times 10^{-19} \times 0.0021 \times 10^{12}$$

$$= 2.69 \times 10^{-8} \text{ cm}^{-1}$$

\therefore Surface:

$$0.3\mu: k = 1.52 \times 10^{-6} \frac{2.1 \times 10^{20}}{2.69 \times 10^{19}} = 1.19 \times 10^{-5} \text{ cm}^{-1}$$

$$0.55\mu: k = 1.22 \times 10^{-7} \frac{2.1 \times 10^{20}}{2.69 \times 10^{19}} = 0.952 \times 10^{-6} \text{ cm}^{-1}$$

$$0.8\mu: k = 2.69 \times 10^{-8} \frac{2.1 \times 10^{20}}{2.69 \times 10^{19}} = 2.1 \times 10^{-7} \text{ cm}^{-1}$$

Cloudtops:

$$0.3\mu: k = 1.52 \times 10^{-6} \frac{1.3 \times 10^{16}}{2.69 \times 10^{19}} = 1.52 \times 10^{-6} \times 4.83 \times 10^{-4}$$

$$= 7.34 \times 10^{-10} \text{ cm}^{-1}$$

$$0.55\mu: k = 1.22 \times 10^{-7} \times 4.83 \times 10^{-4} = 5.89 \times 10^{-11} \text{ cm}^{-1}$$

$$0.8\mu: k = 2.69 \times 10^{-8} \times 4.83 \times 10^{-4} = 1.30 \times 10^{-11} \text{ cm}^{-1}$$

$$H = 1.97 \times 10^6 \text{ cm} \Rightarrow \tau_{\text{ra}} = 23.4$$

$$= 1.87$$

$$= 0.41$$

$$H = 4.3 \times 10^6 \text{ cm} \Rightarrow \tau_{\text{ra}} = \frac{3.2}{1.2} \times 10^{-3}$$

$$\frac{2.5}{9.1} \times 10^{-4}$$

$$\frac{5.6}{2.1} \times 10^{-5}$$

$1.65 \times 10^6 \text{ cm}$
 $H = \leftarrow 10^6 \text{ cm} \rightarrow \tau_{Ra} \sim \begin{matrix} 0.43 & 0.93 \\ 0.20 & 0.075 \\ 0.043 & 0.017 \end{matrix}$

T_{min} :

$0.3 \mu: k = 1.52 \times 10^{-6} \frac{1.0 \times 10^{19}}{0.69 \times 10^{19}} = 1.52 \times 10^{-6} \times 0.372 = 5.65 \times 10^{-7}$

$0.55 \mu: k = 1.22 \times 10^{-7} \times 0.372 = 4.54 \times 10^{-8}$

$0.8 \mu: k = 2.69 \times 10^{-8} \times 0.372 = 1.00 \times 10^{-8}$

\therefore even as high as T_{min} \exists significant yellow Rayleigh scattering.

λ \ AH.	Surface	T_{min}	Cloudtops
0.3 μ	23.4	0.43 0.93	3.2 1.0×10^{-3}
0.4	7.4	0.20 0.075	1.0 2.5×10^{-4}
0.55 μ	1.87	0.075 0.017	2.5 5.6×10^{-5}
0.8 μ	0.41	0.017	5.6 $\times 10^{-5}$

τ_{Ra}

But CH_4 absorption makes $\Theta_0 \neq 1$.

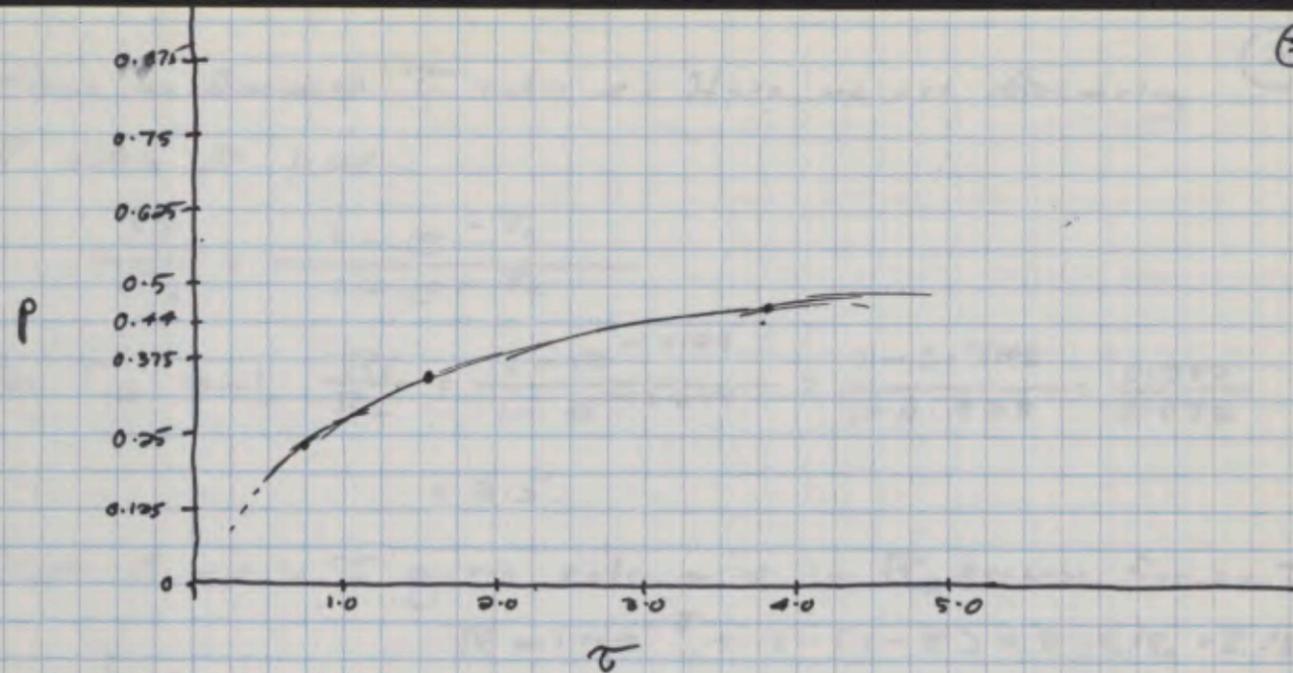
We cannot use 2-stream approx. for Rayleigh scattering: $\beta = \frac{1}{2}$, $\Theta_0 = 1$ because $u \rightarrow \infty$.

In Science 215:504 [p. 516, Smith et al.] Pollock et al.

note, for $A_0 = 0$, $\tau_{Ra} = 3.8 \Rightarrow p = 0.47$;

1.6 0.35

0.75 0.24



Our ratio p_{ix} effectively: $0.55/0.4 \mu\mu$. If we were seeing to T_{min} this would be a τ_{ra} ratio of 3.9 in brightness, certainly excluded. If we were seeing to T_{et} , ratio would be the same, but Rayleigh scattering is insignificant there.

\therefore if Rayleigh begins to be important, ratio of colors ^{in τ_{ra}} of ~ 3.9 would be entirely obvious. \therefore we do not see to level where Rayleigh becomes important \therefore we do not see to T_{min} — blue $\tau_{ra} \sim 0.3$, where contribution to $p \sim 0.1$, also visible [observed $p \sim 0.2$]. $\therefore \tau_{clouds} > 1$ above T_{min} . Assume cloud particles mixed equally in each equi-pressure interval. \exists 16 such intervals between T_{min} + surface. \therefore above surface

$$\tau_{clouds} > 15.$$

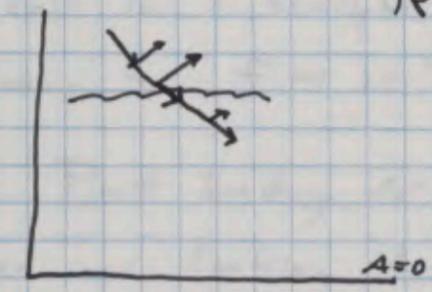
But in Toon, et al. more like mixed equally in every constant Δh .

Above we discussed τ ratio 4. Here we are discussing R ratio of 1.04.

$$\frac{R_1}{R_2} = \frac{1 - e^{-\tau_1}}{1 - e^{-\tau_2}}$$

For T_{min} level, $\frac{R_1}{R_2} = \frac{1 - e^{-0.29}}{1 - e^{-0.075}} = \frac{1 - 0.748}{1 - 0.928} = \frac{0.252}{0.072} = 3.5.$

Ratio of $\tau \sim 4$ in τ gives ratio ~ 4 in R, because, for sm. τ , $R \approx 1 - e^{-\tau} \approx 1 - (1 - \tau) = \tau; R_1/R_2 = \tau_1/\tau_2$



This is even more true when $R_1/R_2 = 1.04$

But @ R is attenuated by a $\tau_{cl,1or2}$:

$$\frac{R_1 e^{-\tau_{cl,1}}}{R_2 e^{-\tau_{cl,2}}} = 4 e^{(\tau_{cl,1} - \tau_{cl,2})} = 1.04$$

$\therefore \Delta\tau \approx 1.4 \therefore$ again, $\tau \approx 1.$

This should be done better, but

$$\tau_{cloud} \gg 10$$

seems safe. Cf. $\tau_{cloud} > 5$ from assumption surface albedos vary between 0.35 + 0.5 + upper limit to detectable contrast of a few % [Smith, et al. Science 212, 163, 1981, p.167].

O/IV ratio is diameter ~ 300 pixels \leftrightarrow 2×2815 km

$\therefore \frac{2 \times 2815}{300} = 18.8 \text{ km/pixel} \sim 20 \text{ km/pixel}$

Registration not good to better than 2 pixels + no feature believable unless $\geq 2 \times 2$ pixels. \therefore conclusions apply to areas

80 km on side. $\therefore f \sim \frac{6400}{\pi (2815)^2} = 2.5 \times 10^{-4}$

Holes show up as dark spots (violet in denominator).

There are some apparent dk. spots, biggest being $\sim 1 \times 3$ pixels in S hemisphere. \therefore safe to limit con-

clusion to $f \sim 10^{-3}$, down to level where color ratio becomes detectable.

But bndry N. polar hood shows dark!

Are we looking to greater depth here?

Does not show in O/CH₄ ratio, but possibly because entire N. polar region very dark. This in turn \Rightarrow N. polar region dk. in orange as seen in pix directly

O/IV: brt N hemisphere } roughly speaking
O/Me: brt. S hemisphere }

Consistent if : (a) $\tau_{\text{ice}} \ll 1$ everywhere

(b) Clouds darker in N. hemisphere

(c) Clouds higher in N. hemisphere, except

(d) N. polar collar low

In highest resol. pic. ~ 1 km/lp

$$f \sim \frac{1}{\pi (2515)^2} \sim 4.02 \times 10^{-8}$$

f ~ 10⁻⁷ for 50% of disk

at altitudes above ~ 300 mb, midway between T_{min} + surface

In VI FDS 34883.07(B), .15(O), .23(G), Squires + I find for 3x3 pixel avgs.:

<u>Position</u>	<u>O / B</u>
Center, S. Hemisphere	1.62
Equatorial \triangleleft , just on S. edge	1.64
Center, N. Hemisphere	1.80
N. Hemisphere, $\frac{2}{3}$ distance from equator to pole	1.80
N. polar collar	1.33:
N. polar limb	1.14:

These nos. are perfectly consistent w. FDS 34915.32 pic. \triangleleft showing disk. S. hemisphere, but N. " + disk. N. polar collar in O/V

For V_a FDS 43934.20(V), .26(B), .32(G)

GIV

<u>Position</u>	<u>GIV</u>
Nr. apparent S. pole	1.61
S. hemisphere, $\frac{1}{2}$ way to equator from S. pole	2.37
Just S. equator	2.44
Equator	2.49
Just N. equator	2.54
N. Hemisphere, $\frac{1}{2}$ way from equator to N. pole	2.62
N. Hemisphere, $\frac{2}{3}$ way from equator to N. pole	2.51
N. polar collar	2.29
Just S. of N. pole	1.83
Nr. apparent N. pole	1.66

Polar collar not resolved, but consistent w. pic. of color ratio: limb-darkening everywhere & continuous brightening S \rightarrow N along central meridian.

What does ratio limb-darkening mean? \checkmark image significantly brightened at limb because of Rayleigh scat. in long tangential slant path? $\therefore \tau_{Ra, \text{slant}} \sim 3 \implies \tau_{Ra, \text{normal incidence}} \sim 3/20 = 0.15$ at $0.4 \mu\text{m}$
This would imply that at center disk we see to

(2) 66. (a) 2.2. (b) 2.2. (c) 2.2. (d) 2.2. (e) 2.2. (f) 2.2. (g) 2.2. (h) 2.2. (i) 2.2. (j) 2.2. (k) 2.2. (l) 2.2. (m) 2.2. (n) 2.2. (o) 2.2. (p) 2.2. (q) 2.2. (r) 2.2. (s) 2.2. (t) 2.2. (u) 2.2. (v) 2.2. (w) 2.2. (x) 2.2. (y) 2.2. (z) 2.2.

Pressure (mb)	Altitude (km)	Notes
12.1	26.35	Normal incidence cloudtop
5.5	28.15	Monochromatic images show almost no limb darkening
2.2	30.0	Unless strongly stretched
0.7	31.8	Absorbing clouds should be strongly limb-darkened in O light
0.2	33.6	Perhaps a mix of the 2 effects
0.1	35.4	Is there perceptible limb brightening in strongly stretched V images?
0.05	37.2	Does the limb darkening agree with what we expect in adiabatic atmosphere?

Notes: The limb darkening is consistent with the adiabatic atmosphere model. The limb brightening is not observed in the V images, but is observed in the O images. This suggests that the limb brightening is due to the presence of absorbing clouds.

What does the limb darkening mean? It is a measure of the temperature gradient in the atmosphere. The limb darkening is due to the fact that the temperature is lower at the limb than at the center of the disk. This is because the limb is further from the center of the sun, and therefore receives less radiation.

pressure level $\sim \frac{1}{2}$ that at T_{min} ; i.e., to about 50 mb or ~ 2635 km altitude. But this is in gross disagreement with limb measures showing normal incidence cloudtop at 2815 km. Yet monochromatic images show almost no limb darkening, unless strongly stretched. But absorbing clouds should be strongly limb-darkened in O light, so perhaps a mix of the 2 effects. Is there perceptible limb brightening in strongly stretched V images? Does the limb darkening agree with what we expect in adiabatic atmosphere?

Notes: The limb darkening is consistent with the adiabatic atmosphere model. The limb brightening is not observed in the V images, but is observed in the O images. This suggests that the limb brightening is due to the presence of absorbing clouds.

Melting the Surface of Titan. II.

After conversation E. Shoemaker, 5/6/82

In Science 215, 504 [p. 520, 1982], Table 2 shows a frequency Γ for 10 km crater produc. on T: corresponds to 0.5 km object making crater ~ 1 km depth.

Cumulative statistics impacting objects assume slope -2.2.
 \therefore objects twice as big arrive $2^{-2.2} = 0.22$ times less frequently.

$$\therefore 1 \text{ km: } \Gamma = 0.13 \times 10^{-14} \times 0.22 \approx 0.03 \times 10^{-14} \\ = 3 \times 10^{-16} \text{ km}^{-2} \text{ yr}^{-1}$$

$$\times (4\pi R^2) = (4\pi \times 2575^2) = 2.5 \times 10^{-8} \text{ yr}^{-1}$$

$$\therefore \tau_{1 \text{ km}} \approx 4 \times 10^7 \text{ yrs.}$$

Diameter ^{depth} impacting object

Waiting time

<u>Diameter im-</u> <u>acting object</u>	<u>Crater</u> <u>diameter</u>	<u>Crater</u> <u>depth</u>	<u>Waiting</u> <u>time</u>	<u>more exact</u>
8 km	160 km	27 km	3.7×10^9	3.9×10^9
1	80	13	8.2×10^8	8.7×10^8
2	40	7	1.8×10^8	1.9×10^8
1	20	3	$4 \times 10^7 \text{ yrs.}$	4.2×10^7
0.5	10	1.6	8.8×10^6	9.2×10^6
0.25	5	0.8	2×10^6	2.0×10^6
0.125	2.5	0.4	4.4×10^5	4.5×10^5
0.063	1.25	0.2	9.7×10^4	9.8×10^4
0.031	0.63	0.1	2.1×10^4	2.2×10^4

Problem: Gene calculates in 4×10^9 yrs one crater
 2575 km diameter. What's wrong? That's earlier flux.

16 m	312 m	50 m	4.6×10^3
8 m	156	25 m	1.0×10^3

How much CH₄ added directly by impact?

$$r = 1 \text{ km}, [\text{CH}_4] \sim \frac{1}{3} \Rightarrow M = \frac{4}{3} \pi (10^5 \text{ cm})^3 1 \text{ g cm}^{-3} \times \frac{1}{3} \\ = 1.4 \times 10^{15} \text{ g}. \quad r = 10 \text{ km} \Rightarrow 1.4 \times 10^{18} \text{ g}.$$

$$\text{Mass of mass. Titan} = 8 \times 10^3 \text{ g cm}^{-2} \times \pi (2.575 \times 10^8)^2 \\ = 6.7 \times 10^{21} \text{ g}. \quad \sum 1 \text{ km impacts} \sim 10^{17} \text{ g}.$$

\therefore at least in last few $\times 10^9$ yrs, impact contributes only sm. fraction [$\ll 10^{-3}$] T atmosphere — although might be a significant contributor of, e.g., CO or H₂O.

Have here taken Gany mede or Callisto crater diameter? (47)
Depth ratios. Note they have central peaks. Is this why some topography pokes through the tholins?

Speed of a \mathbb{E} in η family $\approx \eta$'s orbital velocity $9.64 \text{ km s}^{-1} \sim 10 \text{ km s}^{-1}$. \therefore need $\sim 4\pi$ more mass than we calculated for 20 km s^{-1} impact $\Rightarrow r \sim 4 \text{ km} \Rightarrow 8 \times 10^6$ yrs, except for $r = D$ problem, p. (44)

$\sim 10^4$ objects in η family \mathbb{E} 's, of which Chiron is 1st member.

\exists 13 or 14 \mathbb{E} 's w. $a(1-e)$ interior $\oplus + a(1+e)$ beyond η . $P \sim 200$ yrs. Once they get to η sphere influence, no longer members of η family.

Fact that greenhouse effect sm. today \Rightarrow characteristic time for decay NH₃ / H₂O greenhouse on T \ll time between major impacts. Can we calculate? Also, remember \exists many smaller impacts capable of penetrating to the ice: w. p. (45) nos., $\frac{1}{2}$ km object penetrates 0.8 km every 2×10^6 yrs.

Transmissivity, Clouds of Titan

Use 2-stream approx. (S+P, JGR 72, 469, 1967)

For $A_g = 0$ (iF covered w. organics, a good approx.):

$$\tau = \frac{4u}{(u+1)^2 e^{\tau_{\text{eff}}} - (u-1)^2 e^{-\tau_{\text{eff}}}}$$

$$u^2 = \frac{1 - \omega_0 + 2\beta\omega_0}{1 - \omega_0}$$

$$\tau_{\text{eff}} = \sqrt{3} u (1 - \omega_0) \tau$$

$e^{-\tau}$ is fraction incident radiation that is neither scattered nor absorbed.

When particle radius $a \gg \lambda/2\pi$,

$$\omega_0 \approx \frac{1}{2} + \frac{1}{2} e^{-2k_p a}$$

1st term representing diffraction forward scattering for lg. particles, 2nd term representing transmission through particle.

~~If $a \approx 0.3\mu$, $a \gg \lambda/2\pi$ not satisfied in visible.~~

~~If bigger particles below, it does. For $a \ll \lambda/2\pi$,~~

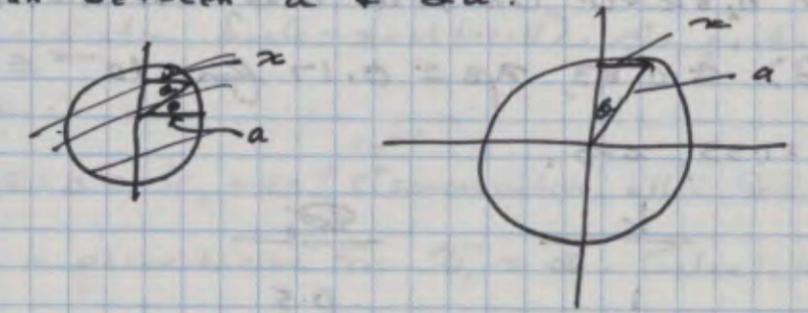
Rayleigh scattering, $\omega_0 \approx 1$ [equiv. of $k_p = 0$]

$$0.55\mu/2\pi \approx 0.088\mu \ll a \text{ when } a \approx 0.3\mu$$

\therefore this eq. OK. \times

Imag. part of complex refractive index we write as k' :
 $I/I_0 = e^{-4\pi k' x / \lambda}$

where x is thickness sample; for a spherical particle, a is some mean between $a + \Delta a$.



$$\sin \theta = \frac{x}{a}$$

$$\langle \sin \theta \rangle = \frac{\int_0^{\pi/2} \sin \theta d\theta}{\int_0^{\pi/2} d\theta} = 2/\pi$$

$$\therefore \langle x \rangle = \frac{2}{\pi} a$$

$$\therefore 4\pi k' \frac{2}{\pi} a / \lambda = 2 k_\lambda a$$

[possible uncertainty of factor $2/(2/\pi) = 1.57$]

$$\therefore 8 k' / \lambda = 2 k_\lambda$$

$$\therefore k_\lambda = \frac{4 k'}{\lambda}$$

Lower transmissivity

Best value [518182] k' (visible) for Titan tholin:

$$k' \approx 0.13$$

$$\therefore k_\lambda = \frac{4 \times 0.13}{5.5 \times 10^{-5}} = 9.5 \times 10^4 \approx 10^5 \text{ cm}^{-1}$$

$\therefore \theta_0 \approx 1/2$: "forward" scattering lobe, w. sidelobes, but no transmission through particle: in effect, lg. opaque particles.

IF $k' \approx 0.10$, $k_\lambda \approx 7.3 \times 10^4 \text{ cm}^{-1}$.

From Hansen + Travis, Fig. 12, $\alpha = 2\pi a/\lambda \approx 4$, $n_i \approx 1.6 \Rightarrow$

$\langle \cos \Theta \rangle \approx 0.65$, $2\beta \approx 0.35$. (rather than 0.5)

This for $n_i \approx k = 0$. On other hand, for $n = 1.33$, $\alpha = 5$,

$\langle \cos \Theta \rangle \approx 0.83$, $2\beta \approx 0.17$ for $10^{-4} \leq k \leq 10^{-1}$.

For $n_i = 1.33$, $\alpha = 5$,

k	$\langle \cos \Theta \rangle$
1	0.5
10^{-1}	0.6
10^{-2}	0.97

These exact calcs. should be redone for T & h lines

$$2\beta = 1 - \langle \cos \Theta \rangle$$

As 1st approx., assume $1/2$ radiation forward-scattered, + $1/2$ scattered isotropically. Then $2\beta \approx 1/2$,

$$\beta \approx 1/4.$$

(25% incident radiation back-scattered). As particles get bigger, β declines.

Calcs.: $2\beta = 0.5$, $k_2 = 10^4$ (conservative, allow for transparent ice), + parameterize for τ , + a . Calculate x -missivity, T , reflectivity, R + absorptivity A .

$\tau \backslash a$	0.1 μm	0.3	1.0	3.0	10.0 μm	30 μm
	0.264	0.136	0.055	0.041	0.041	0.041
3	0.386	0.240	0.125	0.101	0.101	0.101
	0.329	0.624	0.820	0.858	0.858	0.858
10	0.018	0.0015	6.4×10^{-5}	2.5×10^{-5}	2.5×10^{-5}	2.5×10^{-5}
	0.421	0.245	0.125	0.101	0.101	0.101
	0.562	0.754	0.871	0.899	0.899	0.899
30	7.9×10^{-6}	3.8×10^{-9}	2.7×10^{-13}	1.6×10^{-14}	1.5×10^{-14}	1.5×10^{-14}
	0.421	0.245	0.125	-	-	-
	0.579	0.755	0.874	-	-	-
100	1.6×10^{-17}	1.0×10^{-28}	-	-	-	-
	0.421	-	-	-	-	-
	0.579	-	-	-	-	-

Moving 2β from 0.5 \rightarrow 0.25 changes results only slightly, unless $1 - \langle \cos \Theta \rangle \ll 1$.

This is just case expected (Hansen & Travis) for $n \approx 1.65$
 $\rightarrow a \rightarrow \infty$:

an example:
 Analytically, $2\beta = 1/4, \theta_0 \approx 1/2,$

$$u^2 = \frac{0.5 + 0.25 + 0.5}{0.5} = \frac{0.625}{0.5} = 1.25$$

$$u = 1.12, (u+1) = 2.12, (u-1) = 0.12.$$

$$\tau_{eff} = 3^{1/2} = 1.12 \times 0.5 \tau_1 = 0.97 \tau_1.$$

$$\therefore R = \frac{2.12 \times 0.12 [e^{0.97\tau_1} - e^{-0.97\tau_1}]}{4.49 e^{0.97\tau_1} - 0.0144 e^{-0.97\tau_1}}$$

For $\tau_1 \gg 1,$

$$R = 0.057. \text{ For } ak_2 \rightarrow \infty$$

Now, if we fix R , + specify $\tau_1 \gg 1,$

$$R \approx \frac{u-1}{u+1} \approx 0.2. \therefore u-1 = 0.2u + 0.2$$

$$0.8u = 1.2, u = 1.5$$

$$\therefore 2.25 = \frac{1 - \theta_0 + 2\beta\theta_0}{1 - \theta_0}$$

$$\text{Specify } 2\beta = 1/2. \therefore 2.25 = \frac{1 - \theta_0 + 0.5\theta_0}{1 - \theta_0} = \frac{1 - 0.5\theta_0}{1 - \theta_0}$$

$$\therefore 2.25 - 2.25\theta_0 = 1 - 0.5\theta_0$$

$$\therefore 1.25 = 1.75\theta_0 + \theta_0 = 0.71$$

$$\therefore 0.71 = 0.5 + 0.5 e^{-2k_2 \times 3 \times 10^{-5}}$$

$$\therefore 0.21/0.5 = e^{-6 \times 10^{-5} k_2} = 0.42$$

$$\therefore 6 \times 10^{-5} k_2 = 0.87$$

$$\therefore k_2 \sim 1.45 \times 10^4 \text{ cm}^{-1}$$

\therefore if we adopt this n + experimental tholin $k_2 = 7.3 \times 10^4 \text{ cm}^{-1}$,
 mixing ratio organic ices/tholins ≈ 5 .

Titan may be the only object in the solar system which is pitch black at its surface. Visibility, however, is probably good. \therefore take searchlights.

$\tau \sim 10^{-2}$ for haze; 10^{-4} for CH_4 absorption?

\therefore The observed R Titan, the conclusion that $\tau_{\text{clouds}} \gg 1$, + the measured particle sizes $\Rightarrow k_x \sim 10^4 \text{ cm}^{-1}$, very strongly absorbing particles. Tholins measure $k_x \sim 10^5 \text{ cm}^{-1}$, \therefore allowing for them to be $\sim 10^3$ mix with organic ices in the clouds. It also immediately follows that the surface is dark:

$$\therefore \tau \approx \frac{4u}{(u+1)^2} e^{-\tau_{\text{eff}}} \quad \text{for } \tau_{\text{eff}} \gg 1$$

$$\tau_{\text{eff}} = \sqrt{3} = 1.5(1-0.71)\bar{\sigma}_1 = 0.75\bar{\sigma}_1$$

$$\begin{aligned} \therefore \tau &= \frac{4 \times 1.5}{2.5^2} e^{-0.75\bar{\sigma}_1} \\ &= 0.96 e^{-0.75\bar{\sigma}_1} \end{aligned}$$

- $\therefore \bar{\sigma}_1 = 3, \text{ exp} = 0.11$
- $10, \text{ exp} = 5.5 \times 10^{-4}$
- $30, \text{ exp} = 1.7 \times 10^{-10}$

$\bar{\sigma}_1$	τ
3	0.11
10	5.3×10^{-4}
30	1.6×10^{-10}

Numbers, of course, in good agreement with $0.3 \mu\text{m}$ column of p. (53)

This convolved with a \odot only 10^{-2} as bright as on \oplus . \therefore if $\bar{\sigma}_1 > 10$, it is at most a millionth as bright on T as on \oplus . Cf. flight: $0.07 \times \left(\frac{3 \times 10^5 \text{ km}}{1.5 \times 10^8 \text{ km}}\right)^2 = 2.8 \times 10^{-7} \odot$. \therefore at most = the light on \oplus of the crescent C .

Brief Summary Titan Tholin Revent (5/8/82)

Experimental Results

In visible, $n \approx 1.6 \pm 0.1$; $k \approx 0.1$.

∃ considerable variance in both numbers, due, e.g., to roughness & non-specularity of high-pressure pellet, + lateral composition inhomogeneities in this heteropolymer. Direct transmission of tholin film in Cary 14 (film deposited on microscope slide; thickness measured to be variable across slide) gives ff. results. Range of values is a minimum estimate of error:

λ	k	
0.4 μ	0.11 - 0.19	~ 0.15
0.5	0.13 - 0.21	~ 0.17
0.6	0.05 - 0.07	~ 0.06
0.7	[0.021]	
0.8	0.029 - 0.036	~ 0.03
0.9	[0.012]	
1.0	0.013 - 0.018	~ 0.03
	[0.008]	
	[0.006]	

What is appropriate mean k ? $\sum_{0.4}^{1.0} k/\lambda = 0.10$

\therefore value on p.51 too high by 30%.

At 2.5 μ k values Oak Ridge + Goddard overlap + agree $\Rightarrow k$ not too inaccurate. Only regions where k is as lg. as in the visible are

6 μ $k \approx 0.25$

More E applied, I get k . Arakawa: material same everywhere, but g greater closer to discharge.

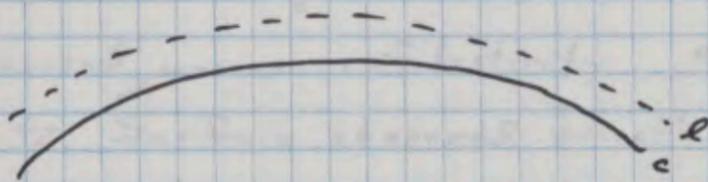
\therefore nr-ir phy; between CH₄ bands has a chance of seeing the surface! Nr-ir phy = surface features. Nr-ir spectrometry = org. chem.

1.2 μ	0.003
1.4 μ	0.002
> 1.6 μ - 2.0 μ	$< 10^{-3}$

1/2 of \odot spectrum at $\lambda > 0.7 \mu$; that's the radiation that mainly heats the surface.

$$\lambda > 15 \mu, \quad k \sim 0.2.$$

This is the value at $17 \mu \Rightarrow$ clouds far from τ transparent here. Indeed, τ so many organics that absorb here, arranging a window is probably impossible. Much more likely:



A detached limb haze of one of the organics is semi-transparent at $17 \mu \pm 1 \mu$ & lives in a region where $T > 94^\circ K$. At 17μ we get a small increment of thermal emission from the layer:

$$T_{eff} = T_l e^{-\tau} + T_c (1 - e^{-\tau})$$

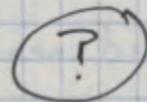
E.g., if $T_c \approx 80 K$ & $T_l = 170 K$,

$$94 = 170 e^{-\tau} + 80 - 80 e^{-\tau}$$

$$14 = 90 e^{-\tau}; \quad e^{-\tau} = 0.156$$

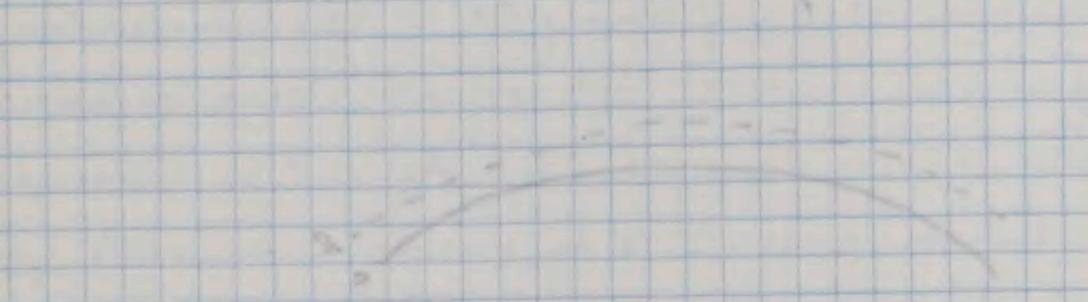
$$\tau = 1.2,$$

easily obtainable. However, T_c very probably $> 94 K$ & mechanism fails. Is there an atmospheric structure solution? \Rightarrow Rayleigh-Jeans assumption above can't Δ nature of discrepancy.



$k \sim 0.25$ at 50 cm^{-1}
 $k \sim 0.05$ at 10 cm^{-1}

is falling very fast. \therefore tholin is an excellent
microwave absorber until about $\lambda = 1 \text{ mm}$, beyond which
it rapidly becomes transparent. Note, however, that there
are Kramers-Kronig values, ϵ will Δ when ϵ or
values are added [$\int \frac{\epsilon''}{\omega - \omega'}$ necessary].



Measured microwave reflectivity $9 \text{ cm}^{-1} < \tilde{\nu} < 22 \text{ cm}^{-1}$
is $\sim 12\%$. Surface observed smooth at these $\tilde{\nu}$.

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

Fresnel normal-incidence reflectance. Here $(n-1)^2 \gg k^2$,
reminding us that R is not a good approach to k
unless k very lg. or n very sm. (here $n \approx 1.3$).

From Goddard Kramers-Kronig n at 10 cm^{-1} , increased to
correct shorter λ errors, I estimate $n \approx 2.0$.

$$\therefore R = 1/9 = 11\%,$$

in excellent agreement w. measured R .

Steve Gingras has measured fca) tholin particles
2 ways: (1) Deposit tholin film on quartz window, &
measure ϵ along a line segment scratch in film
by a moving needle — so-called Alpha Stop
method. It measures how bumpy the road is.

New [5/2/82] Goddard interference fringe measures \Rightarrow
 $\sim 10 \text{ cm}^{-1}$ $n \approx 2.1$ with high reliability. $\therefore R \approx 12.6\%$ ✓

(5)

This done 3 or 4 times. Effective vertical resolution $\sim 0.05 \mu\text{m}$.

(2) Measure SEM's. Effective lateral resolution, $\sim 0.1 \mu\text{m}$. $a_{\text{eff}} \equiv \sqrt{a_{\text{length}} \times a_{\text{width}}}$.

Results convolved by weighting by \propto areas [Double check.]

$$\therefore a \approx 0.3 \pm 0.1 \mu\text{m},$$

on the nose for Voyager results in Smith et al. (1982). Ya. Zeldovich points out wall effects trivial, because area particles very early becomes \gg area walls.

$$\text{E.g. } M = 70 \text{ mg} = 7 \times 10^{-2} \text{ g} \sim \frac{4}{3} \pi a^3 \rho \times N$$

$$\therefore N = \frac{7 \times 10^{-2} \times 3}{4 \pi (3 \times 10^{-5})^3} = 2.1 \times 10^{11} \text{ particles}$$

$$\text{total area } N \pi a^2 = 2.1 \times 10^{11} \times \pi \times (3 \times 10^{-5})^2 \times \pi \\ = 59 \times 10^4 = 590 \text{ cm}^2. \quad \text{10 cm radius flask has area}$$

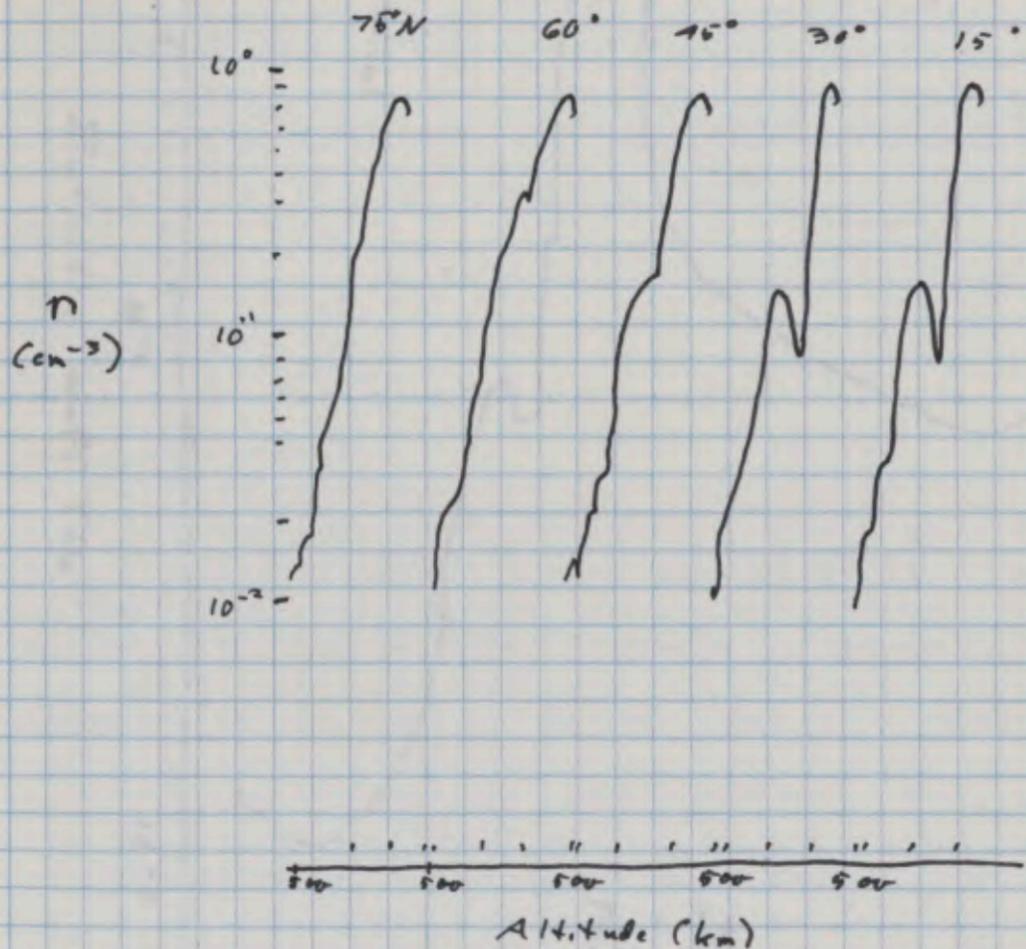
$1 \pi \times 100 = 1200 \text{ cm}^2$. \therefore at least in this expt., area parts $>$ area walls only, half-way through the production of material. Point is still valid: there are not 2 populations; $f(a)$ in number is not bimodal.

IF \exists 1 10μ particle for @ 100 0.3μ parts, compare masses:

$$100 \times \frac{4}{3} \pi (0.3 \mu)^3 / \frac{4}{3} \pi (10 \mu)^3 \\ \therefore 100 \left(\frac{0.3}{10}\right)^3 = \frac{100}{30^3} = \frac{100}{27000} \sim \frac{1}{300} : \text{small particles lose.}$$

\therefore in mass, distrib. is bimodal, ~~but~~ ^{also} in area. But not in no.

Cloud Altitudes: K-Rages



Summary: Tangential edge, main cloud deck, 210 - 250 km.

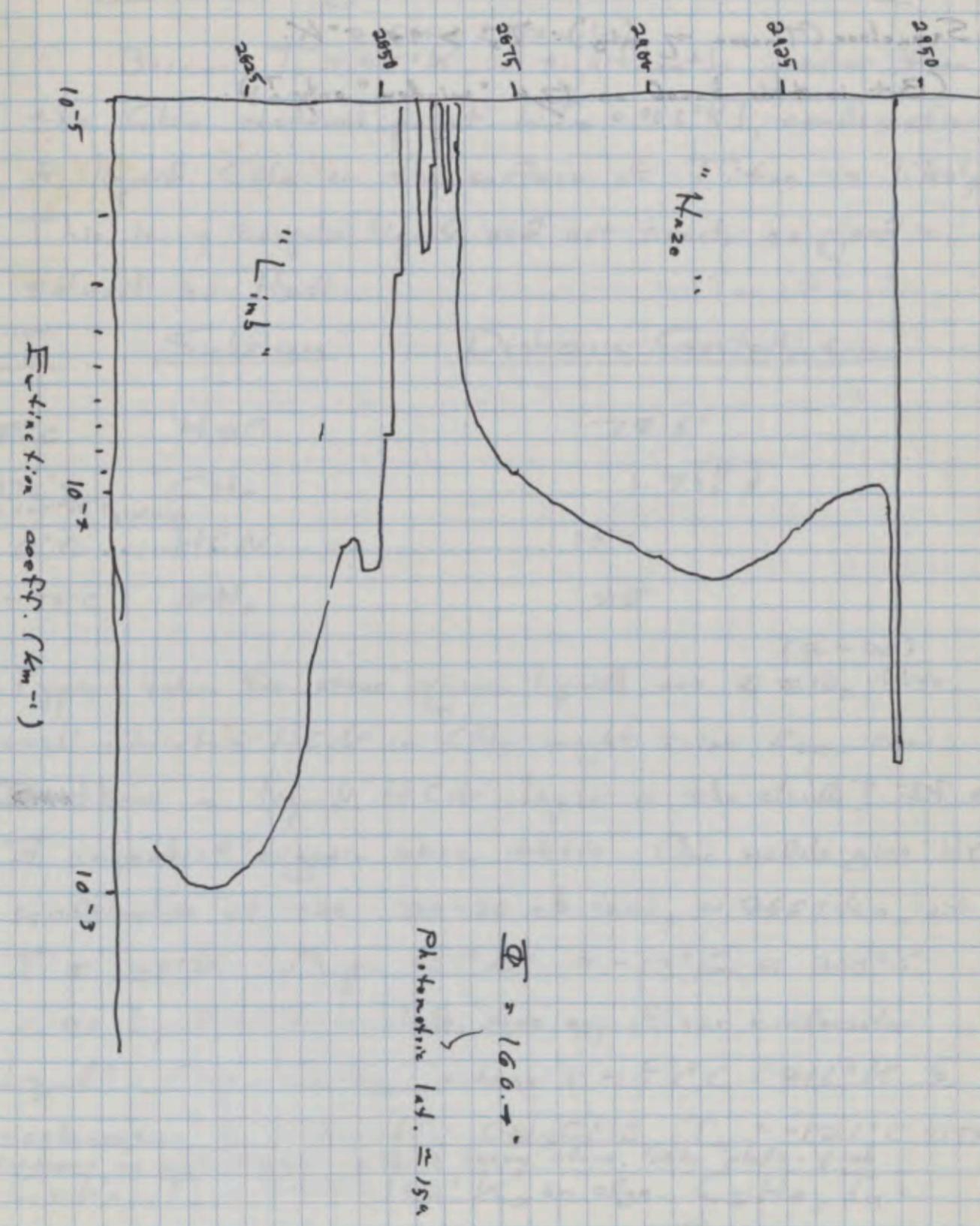
Main detached limb haze, 290 - 360 km

Faint hi-alt. hazes, 440 - 510 km,
upper limit to be determined

Some evidence on night side for hazes in 350 - 400 km range.

K. Rages is checking at what altitude cloud opacity is in fact zero Does it match our predictions?

For hi-resol. VI limb pic (Fig. 10, Smith et al., 1991) (72)



Samuelson (Tucson mtg.): $T_s > 94.5^\circ\text{K}$.

(But is this based on 17μ "window" only?).

Floating Organics on the Oceans of Titan?

Because $T_s \approx 95^\circ\text{K}$ is significantly greater than the CH_4 ^{triple} critical point [$T_c = 90.6^\circ\text{K}$], condensation of liquid CH_4 on the surface of Titan is likely. This is a nonpolar liquid and not nearly as good a solvent as H_2O .

<u>T</u>	<u>Substance</u>	<u>Dielectric Constant, ϵ</u>
25°C	H_2O	78.5
-173°C <small>$\approx 100^\circ\text{K}$, liquid range</small>	CH_4	1.7 (0)
0°C	HCN	158
-78°C	NH_3	25

Typical values for other organic liquids are $\epsilon \approx 10$. Note small admixture HCN in CH_4 might raise ϵ_{CH_4} some. (2-20)

Is there a liquid HCN layer in the clouds? If so, HCN important organic chem. there. Our models give HCN condensation at the 20-30 mb level, $\approx 2660\text{ km}$, at $T \approx 130^\circ\text{K}$. M.p. $\text{HCN} \approx -13^\circ\text{C} \approx 260^\circ\text{K}$.

\therefore no liquid HCN in clouds. Are any of our condensates liquid? M.p. C_8H_{18} , octane = $-57^\circ\text{C} = 216^\circ\text{K} >$

condensation $T \approx 170^\circ\text{K}$. CH_3CHO $T_m = -121^\circ\text{C} = 152^\circ\text{K}$; condenses as solid if typical up for 3 heavy atoms. 'Also' phdis. prob.

C_2H_6 , $T_m = -81^\circ\text{C} = 192^\circ\text{K}$, on edge. C_2H_4 , $T_m =$

$-169^\circ\text{C} = 104^\circ\text{K}$; $T_{\text{freezing}} = -181^\circ\text{C} = 92^\circ\text{K}$
 \therefore Ethylene a liquid at surface Titan!

Methane, $T_m = -182.5^\circ\text{C} = 90.6^\circ\text{K}$; Ethane $T_m = 89.9^\circ\text{K}$.

$\therefore \text{CH}_4 + \text{C}_2\text{H}_6$ are liquid ~~in clouds~~ on surface.

In clouds, CH_4 condenses at $\approx 75^\circ\text{K}$, + C_2H_6 at $\approx 83^\circ\text{K}$, both below melting pt. But local meteorology may liquify methane + ethane crystals in clouds temporarily.

Blun, after Pauling: N, O, + F have highest electronegativity relative to H. \therefore they are most likely to form hydrogen bonds, which in turn provide anomalously high melting pts, boiling pts. + heats of vaporization relative to for NH_3 , OH_2 + HF relative to their isoelectronic hydride congeners (because additional energy necessary to break H-bonds in making those state Δ 's.) These properties, + dielectric constant, contribute to the high biological fitness of H_2O , according to L. J. Henderson. But CH_4 has no such anomalous behavior and is an extremely ineffective solvation medium for organic (bio)chemistry.

On pp. C-75 to C-542 of 56th edition of Hubble Phys. Chem., '75-76, about 30 compds/p. are listed properties of $\sim 14,000$ organic compds. It is clear that $\rho > 0.9$ for vast majority + $\rho > 0.8 \text{ g cm}^{-3}$ for almost all. The exceptions tend to be normal H-C's.:

Exp't: Dissolve T + tholin, to extent poss., in liquid CH_4 after ultrasonic fragmentation. Then heat rapidly to rm. temp., add liquid water, stir; then slowly cool to liquid CH_4 temps. again. Then GCMS, atomic absorption analysis, ir spectroscopy, SEM, etc. Then test as microbial metabolite.

Hydrocarbon	ρ
CH ₄	0.424 g cm ⁻³
C ₂ H ₆	0.572
C ₃ H ₈	0.585
C ₄ H ₁₀	0.601
C ₅ H ₁₂	0.626
⋮	⋮
C ₁₆ H ₃₄	0.773,

which is something of an asymptotic limit. ρ_{CH_4} something like that of noble gases: the more bonds, including H-bonds, the tighter the structure.

$\rho_{Ar} \approx 1.28 \text{ g cm}^{-3}$; but $\rho_{H_2} \approx 0.175 \text{ g cm}^{-3}$, 10x less. Incidentally, $\rho_{N_2} \approx 1.25 \text{ g cm}^{-3}$.

\therefore Nat, ~~however~~ ^(very nearly) almost all organics sink to the bottom of the CH₄ ocean, leaving the ^{equilib.} v.p. of the ocean as the buffer maintaining atmospheric CH₄ abundance, in face of $2 \times 10^6 \text{ yr}$ photodecomposition timescale. (which follows from CH₄ photodissec. rate of $7.4 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ at $\lambda < 1440 \text{ \AA}$, including Ly α .)

\therefore Atmospheric CH₄ maintained by (a) liquid methane ocean; or, likely to be more minor contributors, (b) excavation through benthic organic sediment, + (c) ice vulcanism (CH₄(H₂O clathrates). (d) CH₄ in \oplus 's is entirely inadequate.

Otherwise, access CH₄ to atmos. impeded + atmos. CH₄ lasts only $< 2 \times 10^6 \text{ yrs}$. Is this an argument for CH₄ oceans?

Virtually no tides or waves in this ocean, dimly illuminated by red sunlight filtered through the unbroken clouds.

How much ocean? If same as or $>$ CH₄ in atmos, $\sim 8000 \times 16$

$$= 1.3 \times 10^4 \text{ g cm}^{-2} [\text{CH}_4] / 0.42 \text{ g cm}^{-3} = 3 \times 10^4 \text{ cm} =$$

$$300 \text{ m} \times 10^{\frac{5}{2}} \text{ mixing ratio} = 30 \text{ m CH}_4. \text{ Most}$$

likely depth, unless we are on unlikely verge of evaporation entire CH₄ ocean, is $\gg 30 \text{ m}$ depth. CF.

\oplus where $\sim 10 \text{ cm}$ equiv. H₂O \uparrow + $\sim 3 \text{ km}$ depth H₂O \downarrow : ratio is 3×10^4 .

Detectable Surface Contrast

Does absence of significant difference between ^{"surface"} features detectable in red + in blue \Rightarrow (a) τ , very lg - even in red, or (b) oceans cover surface, so no continental-sized land masses contrasting with oceans or (c) surface uniformly covered w. organics?

$$p_\lambda = R_\lambda + T_\lambda^2 A_\lambda (1 - R_\lambda) + T_\lambda^2 A_\lambda^2 R_\lambda (1 - R_\lambda) + \dots$$

$$\approx R_\lambda + T_\lambda^2 A_\lambda (1 - R_\lambda)$$

Roughly, if $R_\lambda \sim 0.2$, $T_\lambda \sim 0.1$, $A_\lambda \sim 0.1$, then

$$p_\lambda = 0.2 + 0.8 \times 10^{-3} \approx 0.2,$$

+ surface albedo, A_λ , plays no significant role. Surface contrast would not show even for transmissivities as lg. as 10^{-1} , the probable value in the red. In the blue, it's much worse. Alternatively, reverse the argument, + get limits on $T_\lambda + \tau_\lambda$. Worse in blue than in red (1) because ^{more} of Rayleigh scattering + (2) because of more pure absorption. Maximum surface contrast probably 0.7 (ice) to 0.05 (tholins), but uncontaminated ice very hard to come by. Better is contrast between pure Ctx ocean + tholins.

Visible Albedos

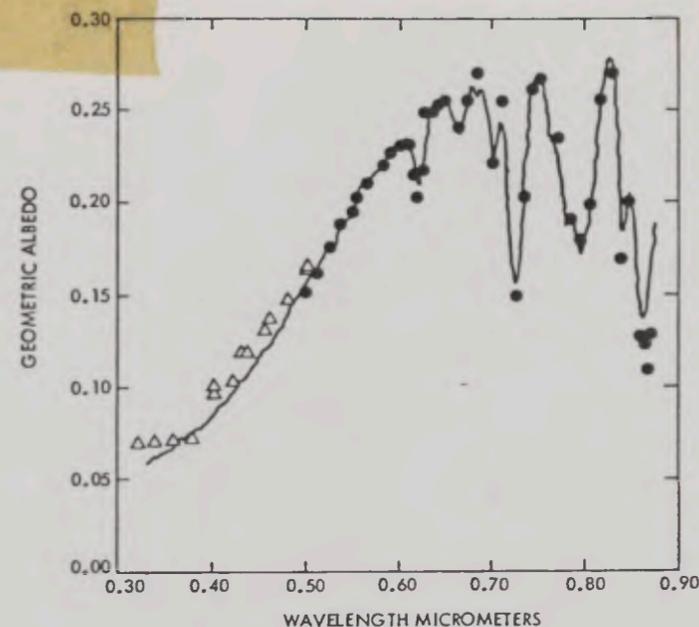


FIG. 6. The geometric albedo as a function of wavelength of Titan for all rotational phase angles. The triangles are the results of McCord *et al.* (1971). All studies have been normalized to the 0.56- μ m geometric albedo reported by Morrison *et al.* (1977). The data of McCord *et al.* are shown only between 0.32 and 0.5 μ m because Younkin's work was done at much higher resolution but only covered the region longward at 0.5 μ m.

solid line: this study

filled circles

R. W. Nelson & B. W. Hapke, Icarus 36, 304-329 (1978)

Note Nelson/Hapke R slightly < McCord's at $\lambda < 5000 \text{ \AA}$.

Also $p < 0.2$ at $\lambda < 5500 \text{ \AA} \rightarrow$ larger k needed from analysis from Table on p. (53)

Note O/B + G/V ratios closely those on pp. (39) + (41).

Do \int over Voy filter bandpasses: V1 O/B, V2 G/V.

CH₄ photodissociation

L. Heroux + H. E. Hinteregger, "Aeronautical Reference Spectrum for Solar UV Below 2000 Å," JGR 83, 5305-08, 1978.

For ⊕

λ 1650 - 1700 Å	$10^9 \frac{\text{ph}}{\text{cm}^2 \text{s}^{-1}}$	$10^{-3} \frac{\text{erg}}{\text{cm}^2 \text{s}^{-1}}$
1650 - 1700 Å	130	1550
1600 - 1650	56	680
1550 - 1600	40	503
1500 - 1550	29	381
1450 - 1500	16	218
1400 - 1450	10	145
1350 - 1400	7.4	107
1300 - 1350	12.4	186
1250 - 1300	4.1	67
1200 - 1250	259	4240
[1216	251	4100
⇒ most CH ₄ phot. energy in H Ly α]		
1150 - 1200	4.4	77
1100 - 1150	0.91	16
1050 - 1100	2.8	52
1000 - 1050	8.1	155
950 - 1000	5.9	119
900 - 950	3.1	68
850 - 900	3.4	78
800 - 850	1.6	38

For τ all values decremented by factor
 $9.54^2 = 91.0$. Reciprocal = 1.1×10^{-2} .

Note measurements apply to \odot min: Apr. 23, 1974.
Conservatively, assume H Ly α same at \odot max. & ignore lg. flares,
because of their brief duration. L. Heroux & J.E. Higgins,
"Summary of full-disk solar fluxes between 250 and
1940 \AA " JGR 82, 3307-3310, 1977 report surprisingly
const. EUV fluxes in $300 \text{\AA} \leq \lambda \leq 1220 \text{\AA}$ over a 7 yr
period.

From Ly α alone, since every photon dissociates CH_4 ,
 $F \sim 2.8 \times 10^9 \text{ phdis cm}^{-2} \text{ s}^{-1}$. Integrating \odot spectrum
 $\lambda < 1450 \text{\AA}$, Reid gets $\sim 3.6 \times 10^9 \text{ phdis cm}^{-2} \text{ s}^{-1}$ [seems about
right]. Lifetime CH_4 from

$$\tau = \frac{\mathcal{N} \text{ mols cm}^{-2}}{F \text{ dissoc. cm}^{-2} \text{ s}^{-1}}$$

$$1.6 \text{ bars} \times \frac{10^6 \text{ dynes cm}^{-2} \text{ b}^{-1}}{1.15 \times 10^2 \text{ cm s}^{-2}} = 1.39 \times 10^4 \text{ g cm}^{-2} \text{ N}_2.$$

$$= 8 \times 10^{-2} \times \frac{16}{28} \times 1.39 \times 10^4 = 6 \times 10^2 \text{ g cm}^{-2} \text{ CH}_4.$$

$$= \frac{6 \times 10^2 \text{ g cm}^{-2}}{1.6 \times 10 \times 1.67 \times 10^{-24} \text{ g mol}^{-1}} = 2.3 \times 10^{25} \text{ mol CH}_4 \text{ cm}^{-2}$$

$$\therefore \tau = \frac{2.3 \times 10^{25} \text{ mol cm}^{-2}}{3.6 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}} = 6.7 \times 10^{15} \text{ s} \quad [1.14 \times 10^{16} \text{ s}]$$
$$= 2.1 \times 10^8 \text{ yrs.} \quad [3.69 \times 10^8]$$

$\therefore > 20$ turnovers in history Titan.

This is direct, mainly Ly α , phdis. CH_4 .

With $g_s = 137 \text{ cm s}^{-2}$, we have $2.0 \times 10^{25} \text{ mols CH}_4 \text{ cm}^{-2}$
 $\tau = 1.76 \times 10^8 \text{ yrs.}$

CO₂ in upper atmos \Rightarrow CO \Rightarrow aldehydes, which we know from our own expts do hot-H chemistry after photolysis. High σ_{phdis} of HCHO + CH₂CHO is why we don't see them. [Could CO₂ in T be derived as our pyrolytic GC/MS CO₂ is from tholins themselves? Must first separate out the oxidation/hydration problem. Note C-O may be extending our 3 μm absorption feature. \therefore need anaerobic expts followed by anaerobic IR spectroscopy -- and if possible, anaerobic GC/MS + probe analysis -- of (a) 90% N₂ / 10% CH₄ / 0.1% CO₂, (b) 90% N₂ / 10% CH₄ / 1% CO₂, (c) 50% CH₄ / 50% NH₃ / 1% H₂O]

Note, measured $\phi \sim 10^{-2}$ for total organics, H₂S hot hydrogen pluchen (possibly 10^{-1} , allowing for shorter λ 's).

Because (a) direct CH₄ photolysis + (b) solar min. F w. no allowance for rare high F events, this is a max. turnover time. Suppose CH₄ is indirectly photolysed by long- λ dissociation of some other constituent [e.g., hot-H chem.], w. quantum yield ϕ . If the process utilizes $\lambda < 2000 \text{ \AA}$ + $\phi_{\text{CH}_4} \sim 0.1$, we have another process of equal magnitude to direct photolysis, $\tau \sim 1 \times 10^9$ yrs. If we utilize $\lambda < 2500 \text{ \AA}$ + $\phi_{\text{CH}_4} \sim 0.1$, $\tau \sim 2 \times 10^9$ yrs. In any case, we must explain why CH₄ still exists.

- Answers: (1) outgassing [cf. my ICT greenhouse paper]
 (2) \Leftarrow impact
 (3) CH₄ \downarrow ocean + high ϕ organics.

Note, if every direct photolysis leads to an organic molecule of molec. wt. ($\mu/16$), $3.6 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1} \times 1.4 \times 10^{17} \text{ s} = 5 \times 10^{26} \text{ mols cm}^{-2} \times \frac{16 \times 1.67 \times 10^{-24}}{16 \times 1.67 \times 10^{-24}} = 1.3 \times 10^4 \text{ g cm}^{-2} \div 1 \text{ g cm}^{-3} = 1.3 \times 10^4 \text{ cm} = 13 \text{ m deep column. } \times (\mu/16)$

If $\lambda < 2000 \text{ \AA}$ + $\phi \sim 0.1$, 26 m column. If $\lambda < 2500 \text{ \AA}$ + $\phi \sim 0.1$, 1300 m = 1.3 km column. Other energy sources seem negligible, although Strobel claims $\sim 10^{10}$ dissociations $\text{cm}^{-2} \text{ s}^{-1}$ + equal magnetospheric part. + uv contributions.

$\lambda < 1440 \text{ \AA}$	$\phi = 1$	13 ($\mu/16$) meter deep column.
$< 2000 \text{ \AA}$	$\phi = 0.1$	26 ($\mu/16$) " " "
$< 2500 \text{ \AA}$	$\phi = 0.1$	1.3 ($\mu/16$) km " "

Note good to a few % in absolute values & probably to < 1% in relative values. (cf. JGR paper)

Note rough agreement of ρ_0 values w. Hansen + Travis results, p. 52.

Note this τ_i is λ -independent; τ_{eff} is λ -dependent.

Transmissivity, Reflectivity Clouds Titan II.

Again 2-stream approx., but using new k 's:

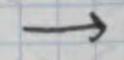
	k'	k_2
Blue	0.16	$1.4 \times 10^4 \text{ cm}^{-1}$
Red	0.04	2.5×10^3
Nr. ir ($\sim 1 \mu\text{m}$)	~ 0.003	120

λ	a	ρ_0	R	τ		
				$\tau_i = 3$	$\tau_i = 10$	$\tau_i = 30$
Blue	0.3 μ	0.72	0.203	1.07×10^{-1}	6.4×10^{-4}	3.0×10^{-10}
	1.0 μ	0.53	0.107	4.8×10^{-2}	4.1×10^{-5}	7.6×10^{-14}
Red	0.3 μ	0.93	0.467	2.9×10^{-1}	2.8×10^{-3}	3.5×10^{-5}
	1.0 μ	0.80	0.267	1.54×10^{-1}	2.3×10^{-3}	1.4×10^{-8}

(cf. calcs. summarized on p. 63.)
P. 52 suggests $p_2(\text{red}) \approx 0.26$, $p_2(\text{blue}) \approx 0.12$.
 \therefore within ± 0.01 in reflection, $\bar{a} \sim 1.0 \mu\text{m}$

Since smaller parts. highest, this is also intuitively reasonable. Does a correct area weighting of our measured distribution function give this result?

Note $\bar{a} = 1.0 \mu\text{m}$, rather than $0.3 \mu\text{m}$ makes approx. $a \gg \lambda/2\pi$ still stronger.



But K.R. argument (based on assumed values k) apparently invalidated by discussion at bottom p. 97. \therefore argument on opposite p. only correct estimate of τ_i until Voy. differential Rayl. scattering or CH_4 ~~trans~~ absorption discussion is completed (JBR? Taby?). [Kathy assumed $k \approx 0.01$ & $a \approx 0.3 \mu$, making ω_0 much too lg. (?)].

[Note contradiction of these values I've calculated w. values in S. Gingras' tables.]

To keep the greenhouse going, need $\geq 1\%$ transmissivity. \therefore if red light is supplying incident flux, & if $\bar{a} \approx 1 \mu$, we can get away with $\tau_i \sim 7$, consistent w. K.R. published results from surface contrast indetectability. But this already assumes Kuiper bands are not extinguishing $>$ tens of % of the incident \odot flux in the red. This caveat still more important in nr. ir.

For $\lambda \sim 1 \mu$, adopting $a \sim 1 \mu$, $k_\lambda = 1.20 \Rightarrow \omega_0 = 0.988$.

τ_i	R	T
3	0.954 0.995 0.954 0.995	1×10^{-2} 6.5×10^{-3}
10	0.954 0.995 0.954 0.995	4.9×10^{-3} 1.4×10^{-5}
30	0.954 0.995 0.954 0.995	7.1×10^{-4} 3.8×10^{-12}

\therefore for $T > 10^{-2}$, $\tau_i < 10$ still; in fact, $\tau_i \leq 3$ must be lg. to For R, ~~interband~~ CH_4 absorption small, $p_\lambda = 0.26 = 0.30$, and $\tau_i \sim 15$. If wings lg, then pass $\tau_i < 10$. bring nr. ir p_λ even to as low as 0.25. In other words, this model requires, for the model to be consistent, substantial absorption in the wings of all nr. ir CH_4 interband regions. ^{(Also,} What is the measured reflectivity at $0.8 \mu \leq \lambda \leq 3 \mu$?) If this is true, can T in nr. ir still be lg. enough to drive the greenhouse? Yes, as long as transmissivity

through τ_{CH_4} is, very roughly,

$$3 \times 10^{-2} \leq \tau_{CH_4} \leq 5 \times 10^{-1}. \text{ Is it?}$$

(See Toby's calcs.)

"A₂" better than "A_λ"

$$\text{Now, } p_\lambda = R_\lambda + \tau_\lambda^2 A_\lambda (1 - R_\lambda)$$

Take $A_\lambda = 0.1, + 0.7; + \bar{a} = 1.0 \mu, \tau_1 = 3$ (most modest case)

Blue: $p_\lambda = 0.11 + [4.8 \times 10^{-2}]^2 \times 10^{-1} \times 0.89 = 0.11$

Red: $p_\lambda = 0.267 + [0.15]^2 \times 0.1 \times 0.73 = 0.269$

Ir: $p_\lambda = 0.995 + [0.018]^2 \times 0.1 \times 0.005 = 0.995$

∴ somewhere in the red is a region of max. bleed-through of surface features.

Red	A _λ	p _λ		
		τ ₁ = 3	τ ₁ = 10	τ ₁ = 30
	0.1	0.269	0.267	0.267
	0.7	0.279	0.267	0.267

∴ if $\tau_1 \leq 3$, a few % surface contrast may show through. ∴ Superimpose Voyager O-filter pix!
But 1% corresponds to $\rightarrow 2\Delta$ difference at most: ∴ impossible.
Also, if clouds are thinner — e.g. at poles — we should see red surface detail.

Better, do this with long t-exposure from Space Telescope.

But is $(1 - R_\lambda)$ term correct, or are we counting and transmission twice?

Then, Blue $p_\lambda = 0.11$

Red = 0.269

Ir = 0.995

Answers are exactly the same.

Note this superimposition is of broad-band λ's, including red + some ir, so optimum region will be covered.

$$s = r\theta = r \frac{\lambda}{D} = 1.5 \times 10^{12} \text{ cm} \frac{7 \times 10^{-5} \text{ cm}}{8 \text{ " } \times 2.54 \text{ cm/"}} = 500 \text{ km}$$

With $R_s \sim 2500 \text{ km}$, # pixels =

$$\pi (2.575 \times 10^3)^2 / (500)^2 = 83 \text{ pixels, over disk T.} \rightarrow$$

For $V1 \times 2$ pix, we are, generally, viewing over many central meridian longitudes in different pix. Are there several that can be precisely registered at some aspect ϕ ? In the likely case that the answer is no, we can (a) stretch individual pix to the limit, or (b) artificially rotate pix so they can in effect be superimposed. Worth doing.

But a several hr. ST exposure (or even $\sim 1^d$) of Titan, with P_{rot} measured in wks., appears to be the best approach. Write Giccoini + include preprint.

Note that a special filter array, emphasizing orange to nr. ir interband regions, would optimize our chances. Each bandpass counted separately, + then X-correlation in imagery. What t-exposure is necessary w. ST to detect a 1% contrast? Is it technically feasible? What instrumentation for T orbiter? Mult. filter nr. - ir ~~radiant~~ imaging systems, + what else?

Should these calcs. be redone for case that @ tholin grain is a nucleus for CH_4 condensation? $a \sim 1 \mu\text{m}$ still, say, but $k' + k_2$ reduced by factor ~ 2 ? $\therefore R$ more + T more. Might be worth doing.

Now for diff. Rayleigh scattering, use p_{Ray} values on p. 31 in place of A_λ : Above surface, roughly,

$0.45\mu \rightarrow \tau_{Ra} \approx 3.8 \rightarrow p'_\lambda = 0.47 = A_\lambda$

$0.56\mu \rightarrow \tau_{Ra} \approx 1.6 \rightarrow p'_\lambda = 0.35$ "

$0.7\mu \rightarrow \tau_{Ra} \approx 0.75 \rightarrow p'_\lambda = 0.24$ "

Assume no surface contribution. Then,

Blue: $p_\lambda = 0.11 + [1.8 \times 10^{-2}]^2 \times 0.47 = 0.11$

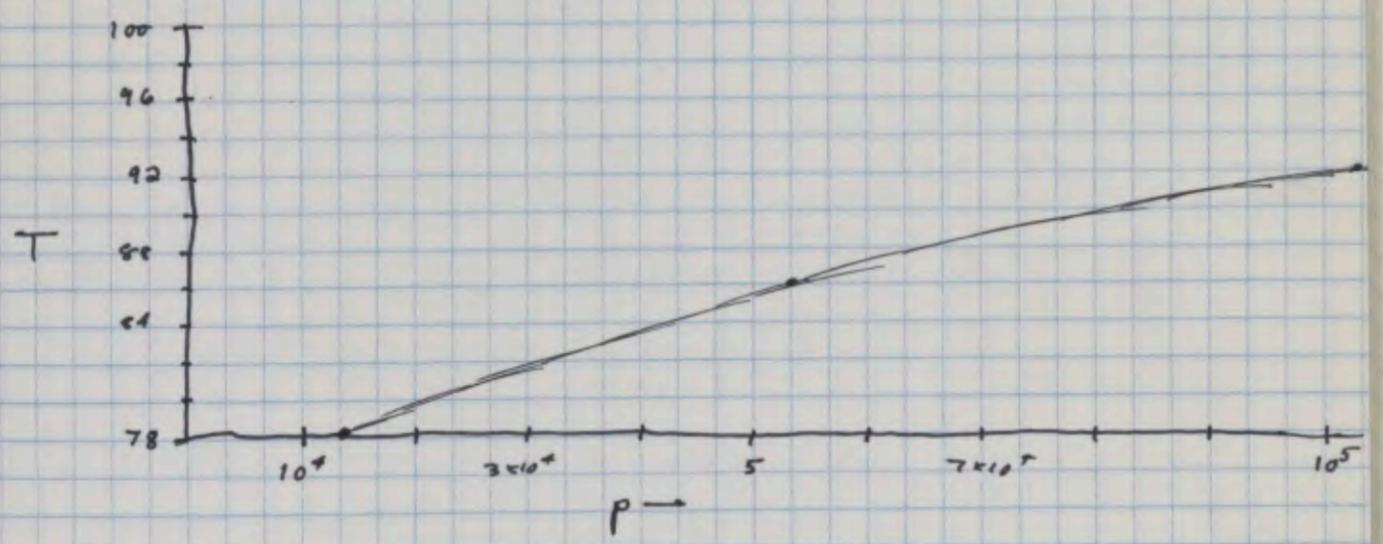
Red: $p_\lambda = 0.267 + [0.154]^2 \times 0.24 = 0.273$

\therefore even with $\tau_s = 3$ we have $< 1\%$ diff. Rayleigh scatt. effect. Perhaps luckier with CH_4 filter.

CH₄ vapor pressure and overburden standoff?

T °C	T °K	p (dynes cm ⁻²)	p (mm Hg)
-205.9 _s	68	1.3 × 10 ³	1
-195.5 _s	78	1.3 × 10 ⁴	10
-187.7 _s	85	5.3 × 10 ⁴	40
-181.4	92	1.3 × 10 ⁵	100
-168.8	104	5.3 × 10 ⁵	400
-161.5	112	1 × 10 ⁶	760

M.p. = -182.5°C = 90.5°K, p ≈ 8.3 × 10⁴ dynes cm⁻²

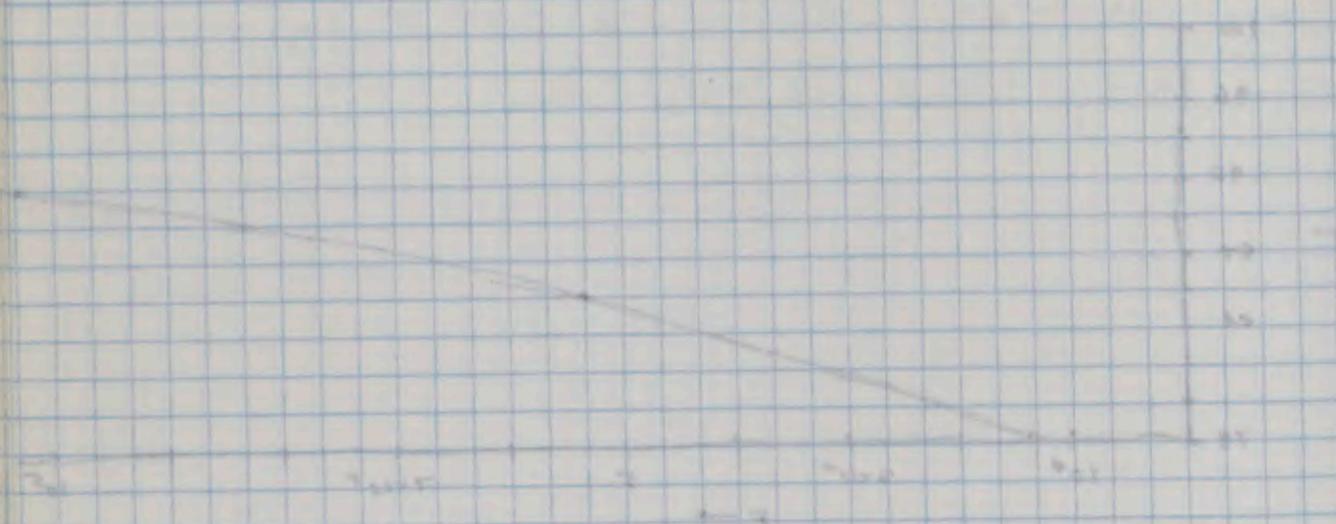


At T_s, equil. p ~ 3 × 10⁵ dynes cm⁻² = $\frac{3 \times 10^5}{1.37 \times 10^2}$
 ~ 2000 g cm⁻² > total M @'s atmos.

CF. 1.66 × 8 ≈ 0.05 ≈ 16 CH₄, within factor 2 ∴ ∴

extrapol. should be ~ 1.5 × 10⁵ dynes cm⁻² ⇒ 1000 g cm⁻² CH₄.

Temperature (K)	Partial Pressure (dynes/cm ²)	Sublimation Rate (g/cm ² /s)
100	1.0 x 10 ¹⁰	1.0 x 10 ⁻¹⁰
150	1.0 x 10 ¹¹	1.0 x 10 ⁻⁹
200	1.0 x 10 ¹²	1.0 x 10 ⁻⁸
250	1.0 x 10 ¹³	1.0 x 10 ⁻⁷
300	1.0 x 10 ¹⁴	1.0 x 10 ⁻⁶
350	1.0 x 10 ¹⁵	1.0 x 10 ⁻⁵



At $T = 100$ K, $P = 10^{10}$ dynes/cm².
 At $T = 350$ K, $P = 10^{15}$ dynes/cm².
 The slope of the line is $\frac{d \log P}{d(1/T)} = -\frac{E}{R}$, where E is the activation energy and R is the gas constant.

Now suppose all CH₄ somehow snatched away. The CH₄ clathrate surface immediately generates a $> 10^5$ dynes/cm² partial pressure. Does this levitate $\sim 10^3$ g/cm² of tholins? Certainly not: $F > 16$ Na.
 Cf. Ice on \oplus . Does a light volcanic dusting stand off from polar cap by this mechanism? No.

Melting the Surface of Titan III

2 questions: (a) what fraction of πR_s^2 Titan has ever been melted; (b) what fraction is, in steady state, apart from CH₄ ocean, exposed by impact cratering before being recovered by tholin fallout?

$0.22^{-1} = 4.54$. Total area melted is

$$\pi [(80 \text{ km})^2 + 4.54(40)^2 + \dots + 4.54^2(20)^2 + \dots]$$

$$= \pi (80)^2 [1 + 4.54/2^2 + 4.54^2/4^2 + 4.54^3/8^2 + \dots]$$

$$= \pi (80)^2 [1 + \frac{4.54}{4} + \frac{4.54^2}{16} + \frac{4.54^3}{64} + \dots]$$

$$= \pi (80)^2 [1 + \sum_{j=1}^N 1.14^j]$$

The sum, of course, diverges -- but slowly. $N=10$ takes us to craters of 25 m depth; i.e., about the minimum steady state tholin depth. Shallower craters don't help us. \therefore total cratered area over $\sim 4 \times 10^9$ yrs is

$$2.0 \times 10^4 \text{ km}^2 [1 + 20.9] = 4.4 \times 10^5 \text{ km}^2, \text{ or}$$

$$\frac{4.4 \times 10^5}{4\pi (2.575 \times 10^3)^2} = 5.3 \times 10^{-3}$$

or $< 1\%$ area Titan.

All CH₄ phd's. in $< 2 \times 10^8$ yrs. in which time a column $> 1 \text{ m} \approx (1/16)$ deep of tholins accumulates. But a few m cover is probably inadequate to cover completely crater rims + central peaks w. tholins, given low-T non-stickiness, prevailing winds, etc. \therefore steady state area in which

craters down to CH₄ ↓ + are still uncovered by tholins is

$$\pi [(20\text{km})^2 + 4.5 \times (10^2) + 4.5 \times (5^2) + \dots]$$

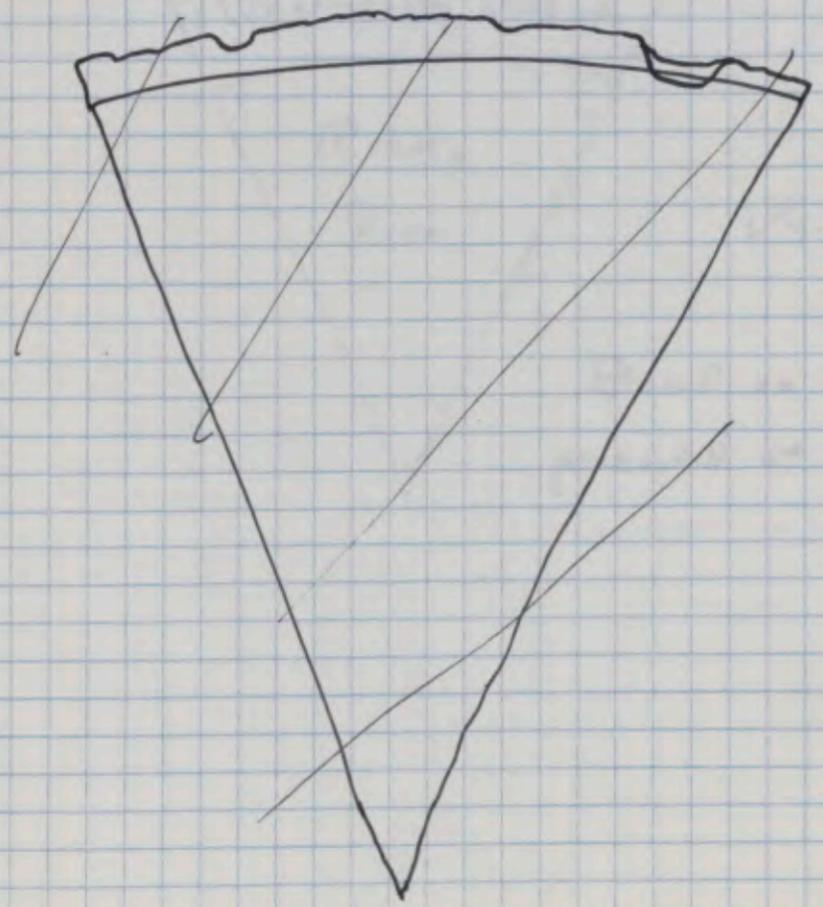
$$= \pi (20\text{km})^2 \left[1 + \sum_{j=1}^{\infty} 1.14^j \right] = \pi (20\text{km})^2 \times 16.1$$

$$\therefore 2.0 \times 10^4 / (\pi (2.975 \times 10^3)^2) = 2.4 \times 10^{-4} \text{ area } T$$

exposed to CH₄ ↓ at crater bottoms in steady state.

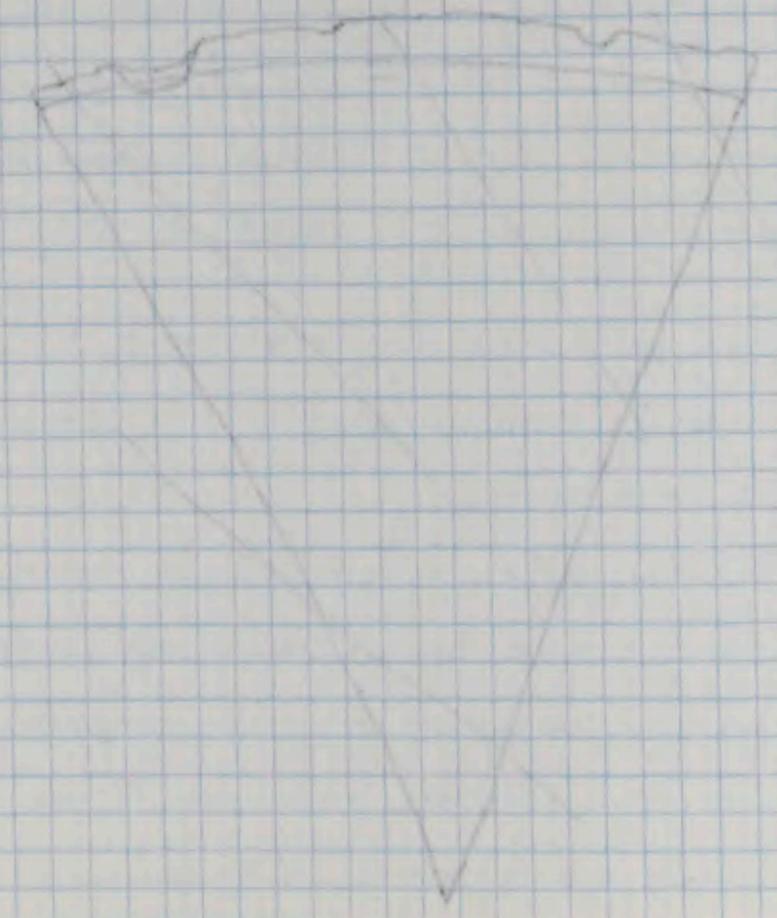
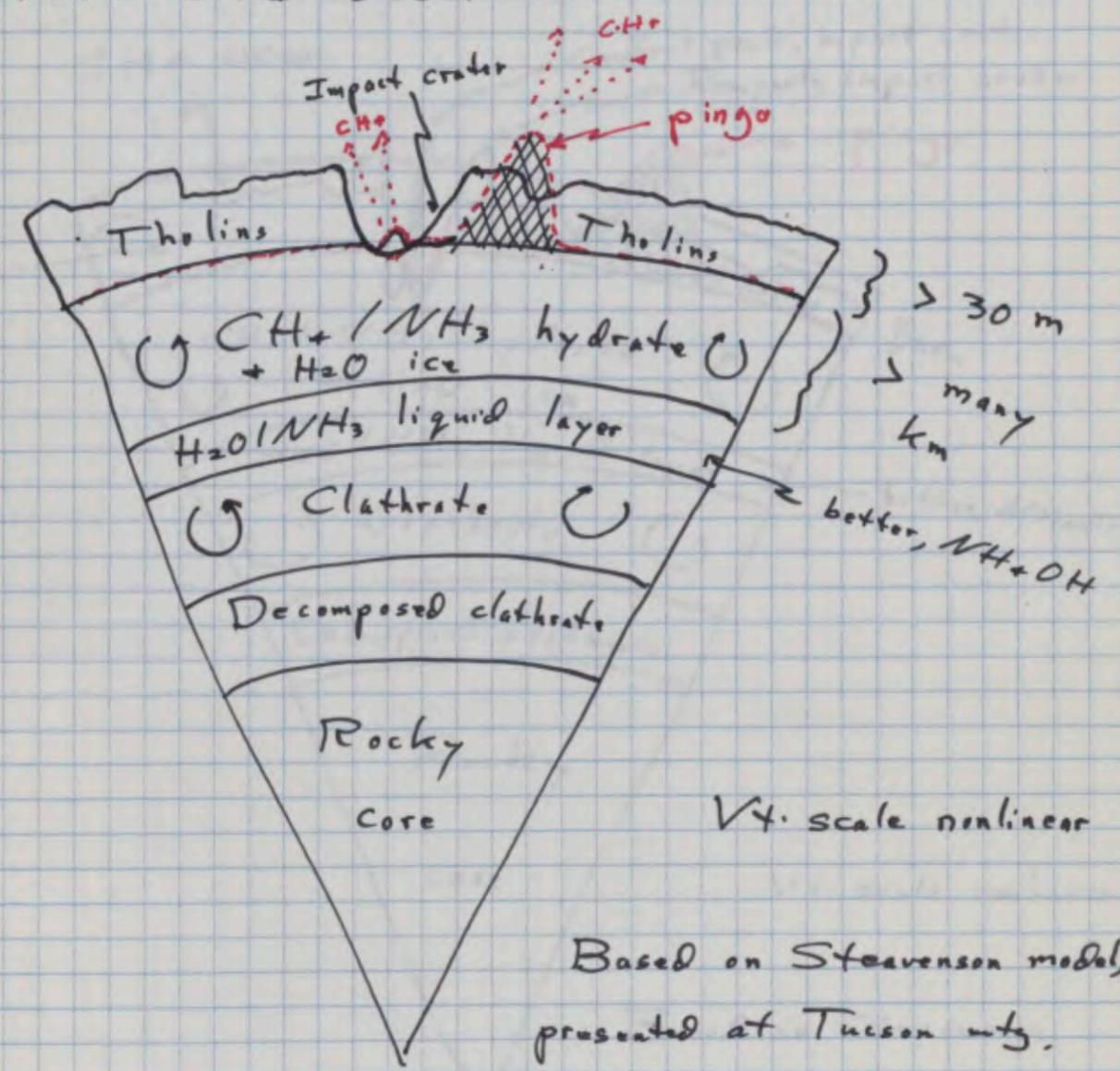
In 2x10⁸ yrs, ~0.02% T gets cratered deeper than the total geol. time accumulation of tholins. These ^{craters} are covered only to a depth of some meters in the 2x10⁸ yrs.

IF phis. of CH₄ is less, cover will be deeper + area w. exposed CH₄ will decline by some tens of %.

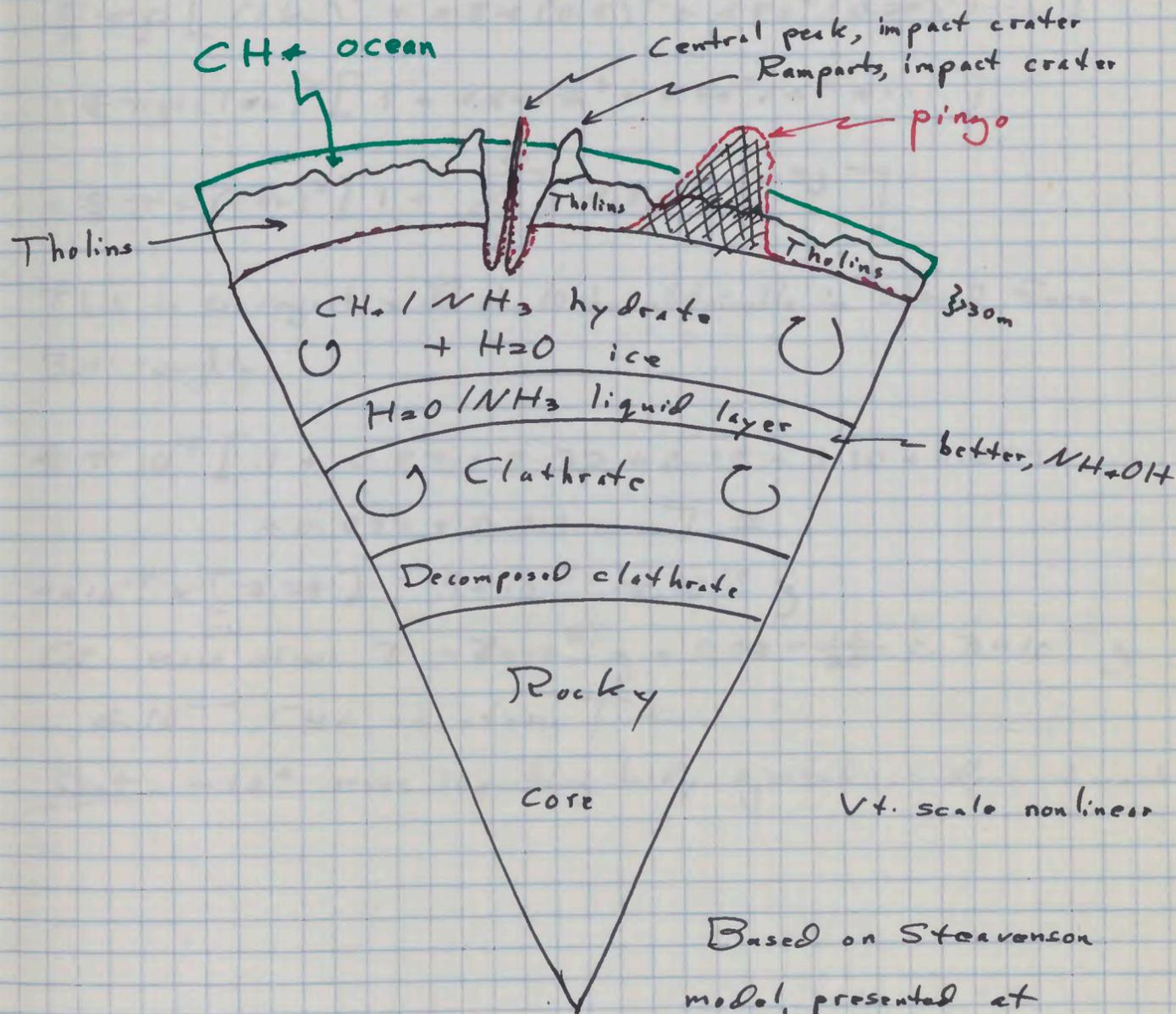


Slices through Titan

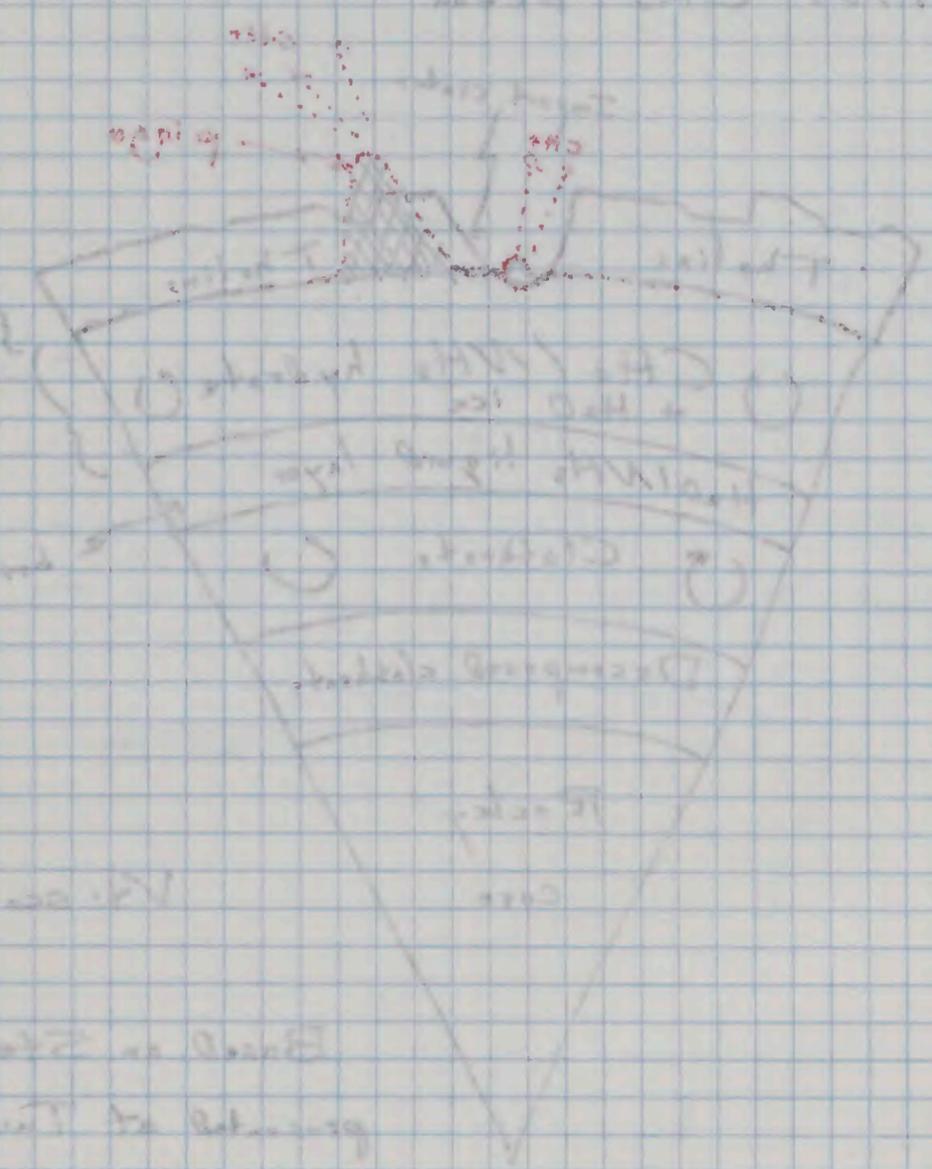
(1) No CH₄ ocean



(2) With CH_4 ocean



Based on Steavenson model, presented at Tucson mtg.



CH₄ added to Titan by cometary impacts

Mass of's in 2x10⁸ yrs is

$$\frac{4}{3} \pi \rho [(1 \text{ km})^3 + 1.5 + (0.5)^3 + 1.5 + 2 (0.25)^3 + \dots]$$

$$= \frac{4}{3} \pi \rho (1 \text{ km})^3 [1 + 1.5 + 1/2^3 + 1.5 + 2/4^3 + \dots]$$

$$= \frac{4}{3} \pi \rho (1 \text{ km})^3 [1 + \sum_{j=1}^{\infty} 1.5 + j 2^{-3j}]$$

This is convergent + Σ should be obtainable in closed form.

But roughly,

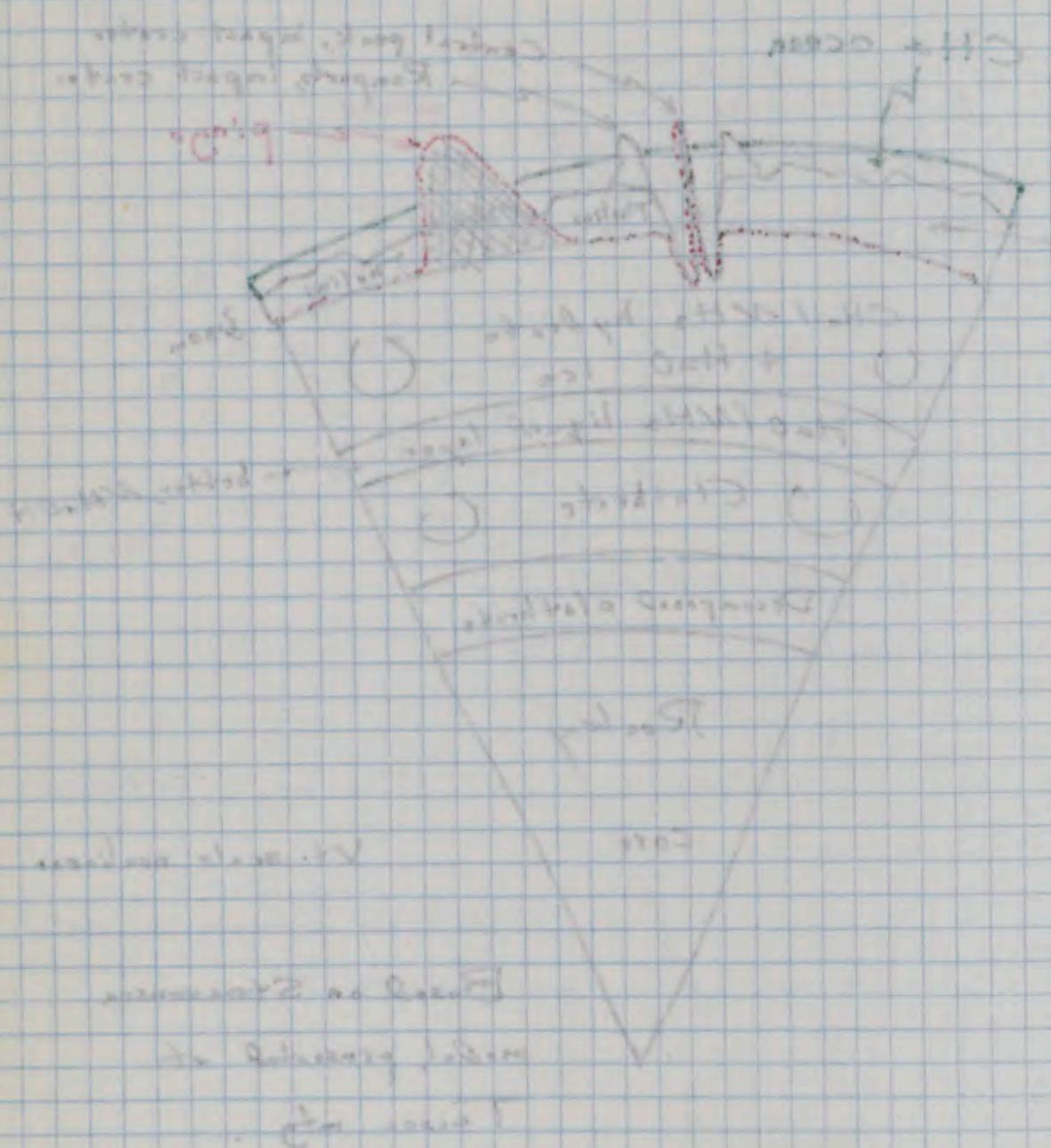
$$\frac{4}{3} \pi 10^{15} [1 + 0.57 + 0.32 + 0.18 + 0.10 + 0.059 + 0.033 + 0.019 + \dots] \approx$$

$$4 \times 10^{15} \times [2.28] = 9 \times 10^{15} \sim 10^{16} \text{ g}$$

$$\text{Cf. mass in } T \sim 2 \times 10^{21} \text{ g} \times 0.08 \times \frac{16}{28} = 3 \times 10^{20} \text{ g}$$

$\therefore < 10^{-4}$ CH₄ in atmos. Titan.

But $\sim 10^4$ mass impacting body ejected. \therefore does it work?



Implications of coagulation and sedimentation times

In Toon, Turco & Pollack [Icarus 43, 260-282, 1980] is a pre-Voyager analysis of Titan's clouds. Short extrapolation of their Fig. 2 gives times for sedimentation through 50 km from 100 mb level (2625 km). Since surface is in fact at 2575 km, this is time to sediment to the surface. For $r = 1 \mu\text{m}$, it is $\sim 30 \text{ yrs} \sim 10^9 \text{ sec}$. The same paper predicts, for particle density $\sim 1 \text{ g cm}^{-3}$ [as suggested by tholin SEM], that the production rate of organics is $\sim 3.5 \times 10^{-13} \text{ g cm}^{-2} \text{ s}^{-1}$. In 30 yrs, this is $\sim 3.2 \times 10^{-4} \text{ g cm}^{-2}$, or an equiv. layer of $3.2 \times 10^{-4} \text{ cm}$ thick. Now, is

$$z \sim 3 \times 10^{-4} \text{ cm}$$

consistent with what is implied by our λ -dependent $\tau_{\text{eff}} = \sqrt{3} \omega (1 - \omega_0) \tau_i$ [note τ_i is λ -independent]?

$$z = \tau_{\text{eff}} / k_\lambda$$

	$\tau_i = 3$	$\tau_i = 10$	$\tau_i = 30$
Blue	$2 \times 10^{-4} \text{ cm}$	$7 \times 10^{-4} \text{ cm}$	$2 \times 10^{-3} \text{ cm}$
Red	$7 \times 10^{-4} \text{ cm}$	$2 \times 10^{-3} \text{ cm}$	$7 \times 10^{-3} \text{ cm}$

\therefore good consistency for $\tau_i = 3$ + not for $\tau_i = 10$.

[τ_{eff} is 1.8 for $\tau_i = 3$, red, + > 3 for other 3 cases.

$\therefore \tau_{\text{eff}} > 1$, + transmission $\propto e^{-\tau_{\text{eff}}}$].

[z, not τ , so no confusion w $\tau \approx 2\pi a / \lambda$]

For $r \sim 0.13 \mu\text{m}$ + for any other process imagined to be rate-limiting, $t \geq 2 \times 10^{10} \text{ s} \sim 600 \text{ yrs} \Rightarrow z_{\text{th}} \approx 6 \times 10^{-3} \text{ cm}$, corresponding to $\tau_1 \approx 30$, which we can exclude on greenhouse grounds.

\therefore Consistency requires

$a \sim 1 \mu$, sedimentation as main fallout process, production rate $\sim 3.5 \times 10^{-13} \text{ g cm}^{-2} \text{ s}^{-1}$, measured tholin k_2 's, and $\tau_1 \approx 3 - 6$, with preference for $\tau_1 \approx 4$. [cf. 10].

Also clouds correspond to a several μm thick layer \Rightarrow several particles to a few tens of particles thick.

For $\tau_1 \approx 3$, $\tau_{\text{eff}} = 3$ in the blue = 1.8 in the red.

We are not talking about huge optical depths. Also, cf. (88), $3.5 \times 10^{-13} \text{ g cm}^{-2} \text{ s}^{-1} \Rightarrow 500 \text{ m}$ layer tholins in 4.5 b.y. \Rightarrow for $\mu = 30$ (C_2H_6) + $\phi \sim 0.1$, $\lambda \approx 2100 \text{ \AA}$, or for $\mu = 30$ + $\phi \sim 0.01$, $\lambda \approx 2600 \text{ \AA}$. The latter suggests photoexcitation of phenyls, or polyenes + collisional energy transport of the activation energy.

1μ part. $\Rightarrow \frac{4}{3} \pi (10^{-4})^3 = 4 \times 10^{-12} \text{ g} = 4 \mu\text{g}$, occupying an area $\pi (10^{-4})^2 = 3 \times 10^{-8} \text{ cm}^2 \Rightarrow 1.3 \times 10^{-4} \text{ g cm}^{-2}$. \therefore to make $3.2 \times 10^{-4} \text{ g cm}^{-2}$ requires a layer 2-3 particles thick if $a \sim 1 \mu$.

In red, $k_2 \sim 3 \times 10^3 \text{ cm}^{-1} \Rightarrow \tau \sim 3 \times 10^3 \times 2 \times 10^{-4} = 0.6$, or roughly,

an optical depth per particle in the red. A few particles + a few optical depths in a vertical line of sight, if $a \sim 1 \mu$. A few tens of particles + a few optical depths if $a \sim 0.1 \mu$.

The Tides of Titan

Because of synchronous rotation ($P_{rot} = 15.95^d$) \exists a standing tide on the γ -facing hemisphere of T.
 By simplest scaling from \oplus ,

$$(h_T / h_{\oplus}) = (M_{\gamma} / M_{\oplus}) (r_{\oplus} / r_{T})^3$$

$$= (95.110.0123) (0.384 / 1.22)^3$$

$$= 2.4 \times 10^2.$$

Max. equilib. lunar tide on \oplus is $\sim \frac{1}{3}$ meter.
 $\therefore h_T \sim 80 \text{ m}.$

More precisely: (Dernett, Icarus 37: 310-321, 1979):
 Amplitude of difference between oceanic + body tides,

$$h = \frac{(M_S / M_T) (R^4 / a^3)}{[1 - \frac{35}{55}] + [1 - (\sigma / \rho)] / \tilde{\mu}}$$

where $M_S = 5.68 \times 10^{29} \text{ g}$, $M_T = 1.34 \times 10^{26} \text{ g}$, $R_T = 2.575 \times 10^8 \text{ cm}$, $a = 1.22 \times 10^{10} \text{ cm}$, $\rho = 1.9 \text{ g cm}^{-3}$, $\sigma = 0.424 \text{ g cm}^{-3}$. $\tilde{\mu}$ is the "effective" rigidity of the core,

$$\tilde{\mu} = 19\mu / 25gR \sim 1$$

where ρ is density + μ rigidity of core Titan.

μ will be related to the bulk density modulus, or isothermal incompressibility, K_0 . But first we need central pressures for T . S. Chandrasekhar (Ap. J. 87, 535, 1938; Intro. ^{to the Study of} Stellar Structure, U. Chi. Press, 1939) derives, indep. of eq. state,

$$\frac{3}{8\pi} \frac{GM^2}{R^4} \leq P_c \leq \frac{3}{8\pi} \frac{GM^2}{R^4} \left(\frac{\rho_c}{\bar{\rho}}\right)^{4/3}$$

$$\bar{\rho} = 1.9 \text{ g cm}^{-3}. \quad \rho_c \leq 5 \text{ g cm}^{-3}, \text{ depending on rocky core.}$$

$$P_c = \frac{GM^2}{R^4} = \frac{6.67 \times 10^{-8} (1.34 \times 10^{26})^2}{(2.575 \times 10^8)^4} = 2.72 \times 10^{11} \text{ dynes cm}^{-2}$$

$$\frac{3}{8\pi} q = 3.25 \times 10^{10} \text{ dynes cm}^{-2} = 32.5 \text{ kbars.}$$

If $\rho_c = 3 \text{ g cm}^{-3}$, $(\rho_c/\bar{\rho})^{4/3} = 1.839$

$\rho_c = 5$ $(\rho_c/\bar{\rho})^{4/3} = 3.633$

\therefore , if $\rho_c = 5 \text{ g cm}^{-3}$

$$33 \text{ Kb} \leq P_c \leq 118 \text{ Kb}$$

Everywhere within \oplus mantle, $\mu \approx \frac{1}{2} K_0$ [see, e.g., ^HJeffreys, The Earth, 5th ed., Cambridge: CUP, 1970]. For pressures $\leq 108 \text{ Kb}$, F. Birch [JGR 57, 227, 1952] finds (Murnaghan - Birch eq. state),

$$K_0 \approx \frac{2P/3}{[(\rho/\rho_0)^{7/3} - (\rho_0/\rho_0)^{5/3}]}$$

Take $\rho = \rho_c = 5 \text{ g cm}^{-3}$, $\rho_0 = 1 \text{ g cm}^{-3}$, $P = P_c = 10 \text{ kb} = 10^{11} \text{ dyn cm}^{-2}$

$$\therefore K_0 \approx \frac{0.667 \times 10^{11} \text{ dynes cm}^{-2}}{[5^{7/3} - 5^{5/3}]}$$

$$[] = 42.75 - 14.62 = 28.1$$

$$\therefore K_0 \approx 0.0237 \times 10^{11} \text{ dynes cm}^{-2}$$

$$+ \mu \approx 1.2 \times 10^9 \text{ dynes cm}^{-2}$$

$$\therefore \tilde{\mu} = \frac{1.9 \times 10 + 1.2 \times 10^9}{2 \times 5 \times 1.37 \times 10^8 + 2.975 \times 10^8} = 0.0646$$

Take $\rho = \rho_c = 3 \text{ g cm}^{-3}$, $\rho_0 = 1 \text{ g cm}^{-3}$, $P = P_c = 10^{11} \text{ dynes cm}^{-2}$

$$\therefore K_0 \approx \frac{0.667 \times 10^{11}}{[3^{7/3} - 3^{5/3}]}$$

$$[] = 12.98 - 6.24 = 6.74$$

$$\therefore K_0 = 0.099 \times 10^{11} \text{ dynes cm}^{-2}$$

$$\mu \approx 4.95 \times 10^9 \text{ dynes cm}^{-2}$$

$$\therefore \tilde{\mu} = \frac{1.9 \times 4.95 \times 10^9}{2 \times 3 \times 1.37 \times 10^8 + 2.975 \times 10^8} = 0.443$$

For upper mantle, $[EB, \theta, \text{Mechanical props. of } F]$

	P	$\tilde{\mu}$	Depth
	0 bars	$0.36 \times 10^{12} \text{ dynes cm}^{-2}$	0 km
4 kb	0.004 Mb	0.71	15
120 kb	0.12 Mb	0.71×10^{12}	350
230 kb	0.23 Mb	1.43×10^{12}	650
391 kb	0.39 Mb	1.83	1000

With rigidity ice, $\tilde{\mu} \sim 6$,

$$h = \frac{103 \text{ m}}{[1 - (3\sigma/5\rho)] + [1 - (\sigma/\rho)]/6}$$

$$[1 - (3\sigma/5\rho)] + [1 - (\sigma/\rho)]/6 \\ = 0.866 + 0.129 = 0.996$$

$$\therefore h = 103 / 0.996 = 103 \text{ m}$$

(124)
 \therefore take $\approx 7 \times 10^{11}$ dynes cm^{-2} , value in range 4 - 120 Kb (15 - 350 km subsurface, upper mantle). Murnaghan - Birch must be inapplicable.

$$\therefore \tilde{\mu} = \frac{19 \times 7 \times 10^{11}}{2 \times 3 \times 137 \times 0.575 \times 10^9} = 62.8$$

$$(M_s / M_T)(R^4 / a^3) =$$

$$(5.68 \times 10^{29} / 1.34 \times 10^{26})(2.575 \times 10^9)^4 (1.22 \times 10^{11})^{-3} \\ = 10,300 \text{ cm} = 103 \text{ m}.$$

$$\therefore h = \frac{103 \text{ m}}{[1 - (3\sigma/5\rho)] + [1 - (\sigma/\rho)]/62.8}$$

$\sigma = 0.42 \text{ g cm}^{-3}$. Take $\rho = 1.9, 3 \text{ g cm}^{-3}$:

$$[1 - (3 \times 0.42 / 5 \times 1.9)] + [1 - (0.42 / 1.9)] / 62.8 \\ = [1 - 0.134] + [1 - 0.221] / 62.8 \\ = 0.866 + 0.012 = 0.878 \\ \therefore h = 117 \text{ meters}.$$

$$[1 - (3 \times 0.42 / 5 \times 3)] + [1 - (0.42 / 3)] / 62.8 \\ = [1 - 0.084] + [1 - 0.141] / 62.8 \\ = 0.915 + 0.014 = 0.929 \\ \therefore h = 111 \text{ meters}.$$

$$\therefore \boxed{h \approx 110 \text{ meters}}$$

Weast, p. E-56: $E_{CH_4} = 1.70$ at $100^\circ K$ for μ wave frequencies. \therefore , assuming (check w. Reid) that $k_{CH_4}^2 \ll (n-1)^2$,

$$R = \left[\frac{\sqrt{E} - 1}{\sqrt{E} + 1} \right]^2 = \left[\frac{0.304}{2.304} \right]^2 = 0.017$$

CH_4 oceans are pitch black at μ wave freqs.
Tholins: Here we know that $k^2 \ll (n-1)^2$, because, e.g., at 11 cm^{-1} , $k \sim 0.01$ + declines to longer λ 's.

~~From~~ ^{In} 30 to 10 cm^{-1} range, $n(\text{tholins}) \approx 2.2 \implies$
 $R = (1.2/3.2)^2 = 0.14$.

\therefore nearly a factor 10 contrast between CH_4 oceans + tholin-covered land on T. \therefore γ -facing hemisphere w. stationary tide should be darker than opposite hemisphere to radar. Comparable contrasts at long vis. + nr. ir windows.

Tides from, e.g., Iapetus? $M = 1.9 \times 10^{26} \text{ g}$, $a = 3.56 - 1.22 \times 10^6 \text{ km} = 2.34 \times 10^6 \text{ km} = 2.34 \times 10^{10} \text{ cm}$. Rhea: $M = 2.49 \times 10^{26} \text{ g}$, $a = (1.22 - 0.53) = 0.69 \times 10^6 \text{ km} = 6.9 \times 10^{10} \text{ cm}$.

~~$\therefore \frac{h_T}{h_0} = \frac{M_I}{M_p} \left(\frac{r_{0I}}{r_{TI}} \right)^3$~~
 $\therefore h_T / h_0 = (M_I / M_p) (r_{0I} / r_{TI})^3$
 $= (1.9 \times 10^{26} / 7.35 \times 10^{25}) (3.84 \times 10^{10} / 2.34 \times 10^{10})^3$
 $= 1.1 \times 10^{-4}$

$\therefore h_T \sim 0.1 \text{ mm}$. Tides of other γ moons have sub-millimeter amplitudes.

+ Surface

Cosmic Ray Reworking of Cloud Tholins

We find that c.r. deposition is concentrated at $r \approx 2650$ km, well into the clouds and ~~near~~ ^{just below} where the $T(z)$ profile becomes isothermal. The z -integrated dissociation rate is $\sim 1 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$. From Toon, Turco, Pollack (1980) the mean fallout time (for $\rho \sim 1 \text{ g cm}^{-3}$) is $\sim 30 \text{ yrs} \sim 10^9 \text{ s}$. How much chemical reworking before fallout?

$10^8 \text{ cm}^{-2} \text{ s}^{-1} \times 10^9 \text{ s} = 10^{17} \text{ dissociations cm}^{-2}$. The cloud loading density (①) is $\sim 3 \times 10^{-4} \text{ g cm}^{-2}$, or $\sim 3 \times 10^{-4} / 4 \times 1.67 \times 10^{-24} = 1.3 \times 10^{19} \text{ atoms cm}^{-2}$. Take 2 bonds/atom on avg. (to avoid counting twice) $\Rightarrow 2.6 \times 10^{19} \text{ bonds cm}^{-2}$.

$\therefore \sim 1$ in 300 bonds broken

while tholins are in clouds. This is \gg bond breakage rate corresponding to ionizing radiation lethal doses.

On surface, c.r. flux down by factor perhaps 10^4 [CHK]. But residence time longer by factor $\sim 10^8$. \therefore it is possible that every bond is broken $30 \times$ during the history of tholins on Titan's surface.

There is also some Arrhenius bond breaking at 95°K , $v. E \sim 5 \text{ eV} = 8 \times 10^{-12} \text{ ergs}$. $\therefore e^{-8 \times 10^{-12} / (1.38 \times 10^{-16} \times 95)} = e^{-600}$, essentially 0. For van der Waals bonds $\sim 0.1 \text{ eV}$, this is $\sim 5 \times 10^{-6}$ bonds broken. \therefore cosmic rays much more potent at reworking ordinary chemistry at surface Titan than is the ambient temperature.

For $\lambda < 2000 \text{ \AA}$, $\phi \sim 0.1$, dissociation rate is $30 \times$ that of c.r.'s.
 $\lambda < 2500 \text{ \AA}$, $\phi \sim 0.1$, " " " $3000 \times$ " " "

\therefore , respectively, 1 in 10 bonds broken, + "every" bond broken $10 \times$ before fallout (except some bonds energies too high to be broken by hot H, etc.).

Nevertheless, major long- λ reworking of tholins in upper clouds + haze.

Analytic Derivation of Contrast Maxima + Minima

Consider the common case that, in the 2-stream approx, $e^{\tau_{eff}} \gg e^{-\tau_{eff}}$, as is commonly the case when (a) $\tau_1 > 1$, (b) τ_0 is not very close to 1, + (c) $\tau_0 \ll (1-\alpha\beta)^{-1} \approx 2$ in our case. \therefore significant optical depth (otherwise no contrast problem anyway) + significant absorption: both ideal for Titan.

$\therefore R = (u-1)/(u+1) \quad + \quad T = [4u/(u+1)^2] e^{-\tau_{eff}}$

$C = \frac{R}{T^2 A_s} = \frac{(u-1)(u+1)^2}{16u^2 A_s} e^{2\tau_{eff}}$

Now $dC/d\lambda = (dC/du)(du/d\tau_0)(d\tau_0/d\lambda) = 0$, + we hope we get 2 roots, a max. + a min. C.

$(u+1)^3 = u^3 + 3u^2 + 3u + 1$

$(u+1)^3(u-1) = u^4 + 2u^3 - 2u - 1$

$\therefore C = (16A_s)^{-1} [u^4 + 2u - 2u^{-1} - u^{-2}] e^{2\tau_{eff}}$

$\therefore \frac{\partial C}{\partial u} = (16A_s)^{-1} \left\{ [2u + 2 + 2u^{-2} + 2u^{-3}] e^{2\tau_{eff}} + 2[u^4 + 2u - 2u^{-1} - u^{-2}] e^{2\tau_{eff}} \frac{\partial \tau_{eff}}{\partial u} \right\}$

$\tau_{eff} = \sqrt{3} u (1-\tau_0) \tau_1$

$\therefore d\tau_{eff}/du = \sqrt{3} (1-\tau_0) \tau_1 + \sqrt{3} u [-d\tau_0/du] \tau_1$

$\therefore d\tau_{eff}/du = \sqrt{3} \tau_1 [1 - \tau_0 - u d\tau_0/du]$

$$\therefore \partial C / \partial u = (\partial A_s)^{-1} e^{2T_{eff}} \left\{ [u + 1 + u^{-2} + u^{-3}] + [u^2 + 2u - 2u^{-1} + u^{-2}] \sqrt{3} \tau_s [1 - \varpi_s - u \partial \varpi_s / \partial u] \right\}$$

Now $\partial u / \partial \varpi_s = (\partial \varpi_s / \partial u)^{-1}$:

$$u^2 = (1 - \varpi_s + 2\beta \varpi_s) / (1 - \varpi_s) = 1 + 2\beta \varpi_s / (1 - \varpi_s)$$

$$\therefore u = [1 + 2\beta \varpi_s / (1 - \varpi_s)]^{1/2}$$

$$\begin{aligned} \partial u / \partial \varpi_s &= \frac{1}{2} []^{-1/2} \frac{\partial}{\partial \varpi_s} [] \\ &= \frac{1}{2} [1 + 2\beta \varpi_s / (1 - \varpi_s)]^{-1/2} \left[\frac{2\beta \varpi_s + 2\beta (1 - \varpi_s)}{(1 - \varpi_s)^2} \right] \\ &= \frac{1}{2} [(1 - \varpi_s) / (1 - \varpi_s + 2\beta \varpi_s)]^{1/2} [2\beta / (1 - \varpi_s)^2] \end{aligned}$$

$$\therefore \partial u / \partial \varpi_s = \partial u / \partial \varpi_s = \beta (1 - \varpi_s)^{-3/2} (1 - \varpi_s + 2\beta \varpi_s)^{-1/2}$$

$$\begin{aligned} \therefore 0 \equiv \partial C / \partial u &= (\partial A_s)^{-1} e^{2T_{eff}} \left\{ [u + 1 + u^{-2} + u^{-3}] + \sqrt{3} \tau_s [u^2 + 2u - 2u^{-1} + u^{-2}] \right. \\ &\quad \left. \times [1 - \varpi_s - u \partial \varpi_s / \partial u] \right\} \beta (1 - \varpi_s)^{-3/2} (1 - \varpi_s + 2\beta \varpi_s)^{-1/2} \frac{\partial \varpi_s}{\partial \lambda} \end{aligned}$$

What can be zero other than { }? $1 - \varpi_s + 2\beta \varpi_s = 0 \Rightarrow \varpi_s = 2$: nonsense. $\partial \varpi_s / \partial \lambda = 0$? Never, especially for Titan. for $2\beta = 1/2$.

$$\begin{aligned} \therefore 0 &= [u + 1 + u^{-2} + u^{-3}] + \sqrt{3} \tau_s [u^2 + 2u - 2u^{-1} + u^{-2}] [1 - \varpi_s + u \partial \varpi_s / \partial u] \\ \partial \varpi_s / \partial u &= \beta^{-1} (1 - \varpi_s)^{3/2} (1 - \varpi_s + 2\beta \varpi_s)^{1/2} \end{aligned}$$

Now $u^2 = [1 - \varpi_s + 2\beta \varpi_s] / (1 - \varpi_s)$

$$\therefore (1 - \varpi_s) u^2 = 1 - \varpi_s + 2\beta \varpi_s = u^2 - \varpi_s u^2$$

$$\therefore u^2 - 1 = \varpi_s u^2 + 2\beta \varpi_s - \varpi_s$$

$$\therefore u^2 - 1 = \theta_0 (2\beta + u^2 - 1)$$

$$\therefore \theta_0 = (u^2 - 1) / (2\beta + u^2 - 1)$$

$$\begin{aligned} \therefore \theta_0 - 1 &= (u^2 - 1 - 2\beta - u^2 + 1) / (2\beta + u^2 - 1) \\ &= -2\beta / (2\beta + u^2 - 1) \end{aligned}$$

$$\therefore 1 - \theta_0 = 2\beta / (2\beta + u^2 - 1)$$

$$[\text{for } \beta = 1, 1 - \theta_0 = (2u^2 - 1)^{-1}]$$

$$\therefore 0 = [u + 1 + u^{-2} + u^{-3}] + \sqrt{3} \sigma, [u^2 + 2u - 2u^{-1} - u^{-2}]$$

$$\times \left[\frac{2\beta}{2\beta + u^2 - 1} - \frac{u(1 - \theta_0)^{3/2}}{\beta(1 - \theta_0 + 2\beta\theta_0)^{1/2}} \right]$$

$$\begin{aligned} \text{last } [] &= \left[\frac{2\beta}{2\beta + u^2 - 1} - \frac{u[2\beta / (2\beta + u^2 - 1)]^{3/2}}{\beta u (1 - \theta_0)^{1/2}} \right] \\ &= \left[\frac{2\beta}{2\beta + u^2 - 1} - \frac{[2\beta / (2\beta + u^2 - 1)]^{3/2}}{\beta^{1/2} (2\beta + u^2 - 1)^{1/2}} \right] \end{aligned}$$

$$= \left[\frac{2\beta}{2\beta + u^2 - 1} - \frac{2}{2\beta + u^2 - 1} \right] = \frac{2(1 - \beta)}{2\beta + u^2 - 1}$$

$$\begin{aligned} \therefore 0 &= [u + 1 + u^{-2} + u^{-3}] + \sqrt{3} \sigma, [u^2 + 2u - 2u^{-1} - u^{-2}] \\ &\times \left[\frac{2\beta}{(2\beta + u^2 - 1)} - \frac{u(1 - \theta_0)^{3/2}}{\beta} \right] \end{aligned}$$

$$\text{Last } [] = \left[\frac{2\beta}{(2\beta + u^2 - 1)} - \frac{u(1 - \theta_0)^{3/2}}{\beta} \right]$$

$$= \left[\frac{2\beta}{(2\beta + u^2 - 1)} - \frac{u^2}{\beta} (1 - \theta_0)^2 \right]$$

$$= \left[\frac{2\beta}{(2\beta + u^2 - 1)} - \frac{u^2 + \beta^2}{\beta(2\beta + u^2 - 1)^2} \right]$$

$$\therefore 0 = [u + 1 + u^{-2} + u^{-3}] + \sqrt{3} \rho \tau, [u^2 + 2u - 2u^{-1} - u^{-2}]$$

$$\times \left[\frac{2\rho}{(2\rho + u^2 - 1)} - \frac{+\rho u^2}{(2\rho + u^2 - 1)^2} \right]$$

$$\therefore 0 = [u + 1 + u^{-2} + u^{-3}] + \sqrt{3} \rho \tau, [u^2 + 2u - 2u^{-1} - u^{-2}]$$

$$\times \frac{2\rho - u^2 - 1}{(2\rho + u^2 - 1)^2}$$

When $2\rho = \frac{1}{2}$, fraction = $\frac{\frac{1}{2} - u^2 - 1}{(\frac{1}{2} + u^2 - 1)^2} = \frac{-\frac{1}{2} - u^2}{(-\frac{1}{2} + u^2)^2} = -\frac{u^2 + 0.5}{(u^2 - 0.5)^2}$

$$\therefore 0 = [u + 1 + u^{-2} + u^{-3}] - 0.866 \tau, [u^2 + 2u - 2u^{-1} - u^{-2}]$$

$$\times \left[\frac{u^2 + 0.5}{(u^2 - 0.5)^2} \right] \quad ; \quad 2\rho = \frac{1}{2}$$

\therefore for $\tau_1 = 3$, take $u = 3.411$.

$$\therefore [4.522] - 2.60 [17.78] \left[\frac{12.13}{123.98} \right] =$$

$$4.522 - 1.523 \approx 0$$

Roots of the boxed eq.:

τ_1	u	θ_0
3	1.040531	0.1419
	3.41115	0.955
10	1.010238	0.0395
	9.602816	0.99455
30	1.00327	0.01294
	26.96153	0.99931

by successive approximations. The lower θ_0 corresponds to a C min.; the lger value to a C max. Since boxed eq. not

$$\therefore \tau_{\text{off}} = \sqrt{3} \times 3.411 \times 0.045 \times 3 = 0.798$$

$$e^{\tau_{\text{off}}} = 2.2 ; e^{-\tau_{\text{off}}} = 0.45. \text{ Ratio is factor } 4.9. \text{ OK.}$$

If $\tau_1 \approx 5$, $u \approx 5.5$, then $\theta_0 = 0.98$, $\tau_{\text{off}} = 0.953$

$$e^{\tau_{\text{off}}} = 2.6 \gg 0.39. \text{ Ratio is factor } 6.7.$$

For transmissivity, $\#$ is $(u+1)^2 e^{2\tau_{\text{off}}} \gg (u-1)^2 e^{-2\tau_{\text{off}}}$, which is still more easily satisfied. e.g., for $u=3.411$, $11.63 \times 2.2 \gg 5.8 \times 0.45$, or $26 \gg 2.6$. This is also true for denominator R . In numerator R , if inequality not quite satisfied, R will be slightly lger than calculated.

\therefore For $\tau_1 = 3$, calc. rough. For $\tau_1 \geq 5$, quite accurate.

linear, it is not true that contrast is maximum at λ of highest ϖ_0 . \therefore at what λ is $\varpi_0 \approx 0.96$ (or a little higher if σ_1 is a little larger than 3)? It's where, neglecting CH₄ absorption,

$$R = \frac{2.411}{1.411} = 0.55$$

$$+ T = \frac{4 \times 3.411}{1.411^2} \times 0.45 = 0.32$$

or, equivalently, please in terms of k' :

$$\varpi_0 \approx \frac{1}{2} + \frac{1}{2} e^{-2k_2 a} \quad (\varpi_0 \geq 0.5)$$

$$2\varpi_0 - 1 = e^{-2k_2 a}$$

$$\ln(2\varpi_0 - 1) = -2k_2 a$$

$$\therefore k_2 = \frac{-\ln(2\varpi_0 - 1)}{2a} = \frac{k'}{\lambda}$$

$$\boxed{k' \approx \frac{\lambda \ln(2\varpi_0 - 1)}{2a}}$$

From $R + T$, λ somewhere in i.r., take $0.9 \mu = 9 \times 10^{-5}$ cm, $a = 1 \mu = 1 \times 10^{-4}$ cm. $k' \approx -0.113 \ln(2\varpi_0 - 1) = \dots$

$= -0.113 \ln 0.92 \approx 9.4 \times 10^{-3} \approx 10^{-2}$. Indeed, with p. (60) values of $k = k'$, around 0.9μ , or a little less. \therefore it windows

at $\approx 0.82 \mu$ or nr. 0.9μ . For other root, $R = \left(\frac{0.04}{0.04}\right)^2 = 0.0196$, somewhere in nr. uv. Take 0.3μ . $\therefore k' \approx -0.025 \ln(-0.714)$.

Box only works when $2\varpi_0 - 1 > 0$, $\varpi_0 > 0.5$. Still, its clearly in nr. uv.

With newer, red values, might be as high as $\lambda \approx 0.6 \mu$

Liquid Methane

J.D. Olson, "The refractive index and Lorenz-Lorentz function of fluid methane," J. Chem. Phys. 63, 474-484, 1975. In ff. table, we have converted mol/l \rightarrow g cm⁻³ by multiplying by 16.000/1000. What correction for \oplus isotopic composition C + H? Atomic wt.

C is 12.0111, H is 1.0080. $\therefore \mu_{CH_4} = 16.0431$. Recorrect for that:

<u>T</u>	<u>p</u>	<u>ρ</u>	<u>n</u>
90.68 °K (triple pt.)	0.121 bars	0.452 g cm ⁻³	1.296
95.00	0.129 bars	0.446	1.292
100.00	0.345	0.439	1.287
105.00	0.566	0.432	1.282
110.00	0.884	0.425	1.277
115.00	1.919	0.418	1.272
119.40	4.37	0.212	1.135
190.56		0.163	1.103 (crit. pt.)

n is measured at 5462 Å. Note 1.292² = 1.669 \approx 1.7, same as purported μ_{vac} value ϵ . Note 0.26/1.6 bars = 12.5% mixing ratio by weight, or $\frac{26}{16} \times 0.125 = 22\%$. $\text{MM} \times \frac{127}{100} = 3\%$.

For surface,

$T = 95 \text{ °K}, p = 0.26, \rho = 0.45 \text{ g cm}^{-3}, n = 1.29$

\therefore all $\rho = 0.42 \text{ g cm}^{-3}$ must be corrected upward by 7%.

$\partial \rho / \partial T \approx 0.007 / 5 \text{ °K} = -0.0014 \text{ (K}^{-1}\text{)}$

L.W. Pinkley, P.P. Sethna and Dudley Williams, "Optical constants of liquid methane in the infrared" J. Opt. Soc. Am. 68, 186-189, 1978.

Measure "near-normal" incidence R_{CH_4} at 28°K in 350-6700 cm^{-1} range; then Kramers-Kronig phase shift analysis. Methods for deriving $n+k$ for CH_4 solid from these results are described. 3 sm. discontinuities nr. 3100 + 1300 cm^{-1} (3.2 + 7.7 μ). Otherwise, R is 1.1 to 1.4%, n is 1.25 to 1.27, + k is 0.01 or less (0.07 at 3000 cm^{-1} + 0.16 at 1300 cm^{-1} , both spikes).

J. F. Marcoux, "Indices of refraction of some gases in the liquid + solid state," J. Opt. Soc. Am. 59, 988-1000, 1969. In Na D light only, optical refractometer. For liquid CH_4 , $n = 1.28 \pm 0.01$ at 111°K (said to be b.p.) + $n = 1.30 \pm 0.01$ at 91°K (n.p.). Also at 91°K, but for the solid, $n = 1.33 \pm 0.01$, same value as for water ice.

The first part of the paper is devoted to a discussion of the
 properties of liquid crystals in the isotropic state.
 The authors discuss the effect of temperature on the
 order parameter and the dielectric constant. They also
 discuss the effect of the presence of impurities on the
 properties of the liquid crystal. The authors conclude
 that the properties of liquid crystals are very sensitive
 to the presence of impurities and to the temperature.
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 that the dielectric constant is very sensitive to the
 presence of impurities.

D. F. Morrison, "The effect of temperature on the
 properties of liquid crystals in the isotropic state."
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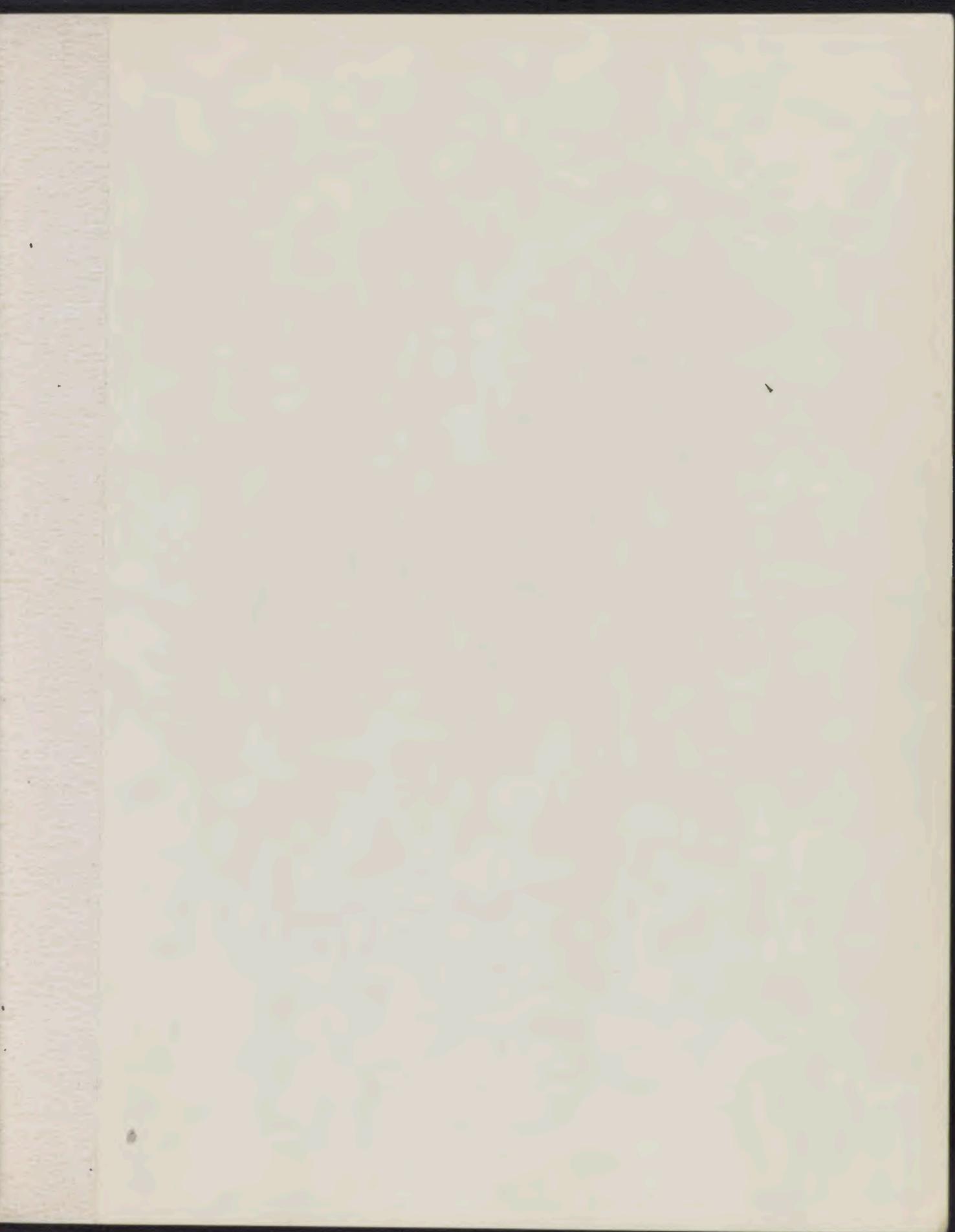
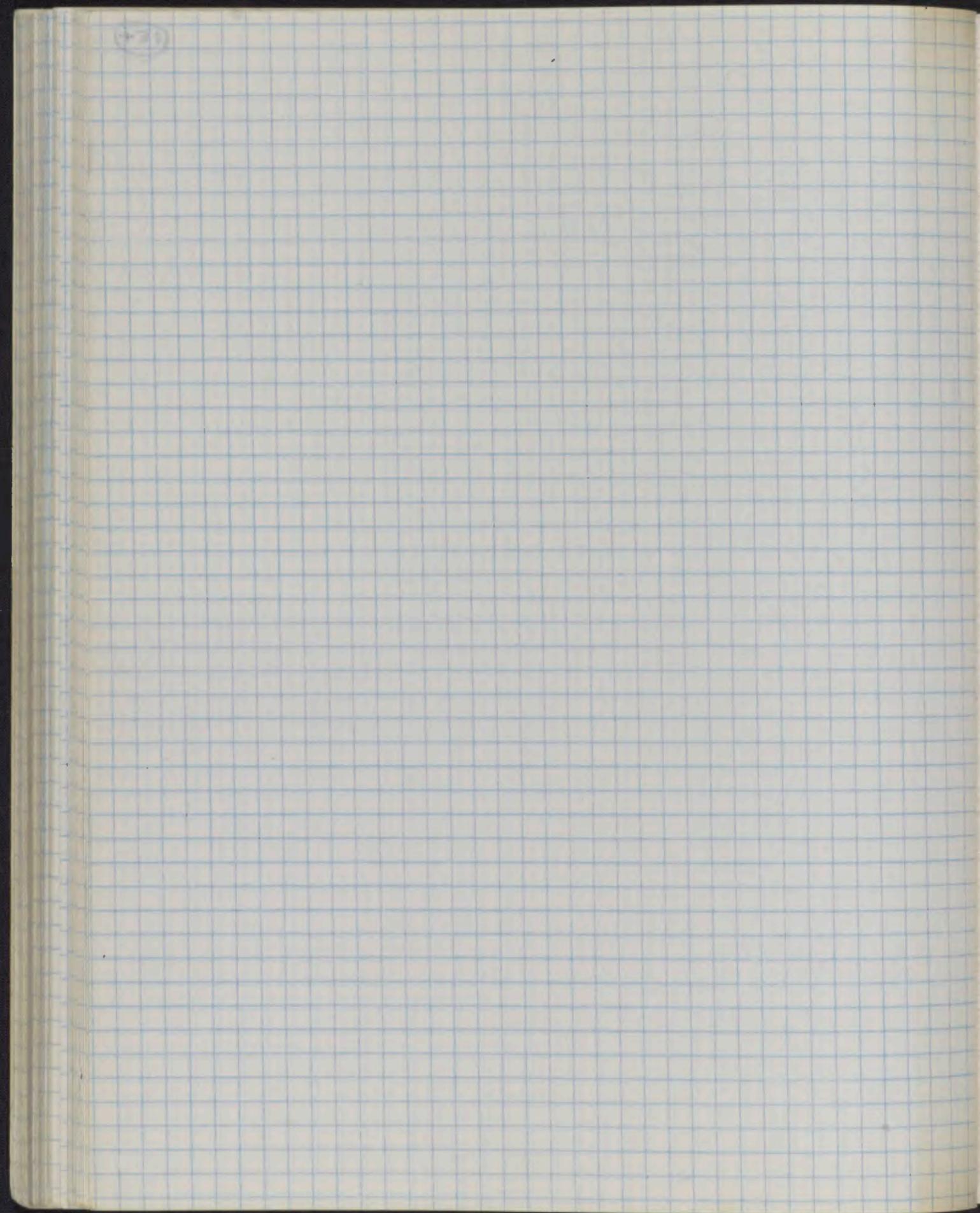
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